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WEIGHTLESSNESS

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INTRODUCTION /4*

The development of cosmonautics poses many new scientific and practical problems for physiology and medicine. These problems are mainly due to the fact that the life and activity of cosmonauts during flight proceed under the specific conditions of weightlessness.

The kinetic and dynamic conditions which are created under the influence of gravitational, inertial and external forces, lend weight to bodies, create the condition of subgravitation (or reduced weight), and weightlessness, are well known [111, 202] and will be discussed here only briefly. The weight of a body is a function of a given mass which is subjected to the action of a given force and the dynamic conditions in which the body finds itself. It has been found that the value which is the shorthand representation for the standard accelerations of the attraction of the Earth's gravity (g_0) is convenient for expressing the acceleration acting on a body and the value which is the standard shorthand representation for the weight or force acting on a body. This is sufficient for establishing a practical system of units in which the unit of acceleration is equal to 1g and the unit of force is 1G. In this sense, weight means that a given mass is subjected to the action of a given force of gravity. Inasmuch as the real force acting on the body and produced by acceleration is equivalent to the weight of the body the symbol may be used in space biology and medicine for representing both the force and the weight. The unit of acceleration (g_0) in this system is always a constant, i.e., 9.81 m/sec^2, while the unit of force varies for bodies with different masses [202].

In all cases of free motion of a body, the force of inertia balances the force of gravitation at any point on the trajectory. The so-called state of "freedom from gravitation" develops. However, this determination is insufficiently accurate for these conditions, since the body is constantly subject to the action of the force of gravitation of the Earth or other heavenly bodies. Therefore, such a state is described as "weightless" or the condition of "zero G", since the resultant of the forces acting on the body and caused by gravitation and inertia is actually equal to zero [185]. /5

*Numbers in the right hand margin indicate pagination in foreign text.

On the other hand, the term "weightlessness" is widely used for describing the subjective impressions of man in situations when he does not have any sensations of his own weight or is in a state of zero G. Other states which are accompanied by a decrease in the sensation of weight, such as immersion in water, a suspended state or conditions that are associated with a decrease in friction, imitate weightlessness more or less exactly. They are used for simulating conditions of weightlessness and evaluating its influence on the human organism, together with bed rest. Although the effects of such influences are based on the interaction of "hypokinesia", i.e., limitation of spatial characteristics of motion and "hypodynamia", i.e., a decrease in its force component, they are not identical to the state of weightlessness as far as determination is concerned. At zero G, the body is completely free of support, weightless and floats freely in space (Figure 1).

The biological effects of zero G, on the basis of the physical characteristic of this state, must be the same, regardless of whether it develops inside /6
or outside the gravitational field of the Earth. However, it has been suggested that inhomogeneity of the force fields may promote the development of intermolecular forces in the organism. Depending on the distance to the heavenly bodies, different effects may be produced. Inasmuch as the study of this problem is of scientific interest under various conditions of biological interactions, the study of the medical aspects of weightlessness is of primary importance for future space flights as well as lunar and planetary expeditions.

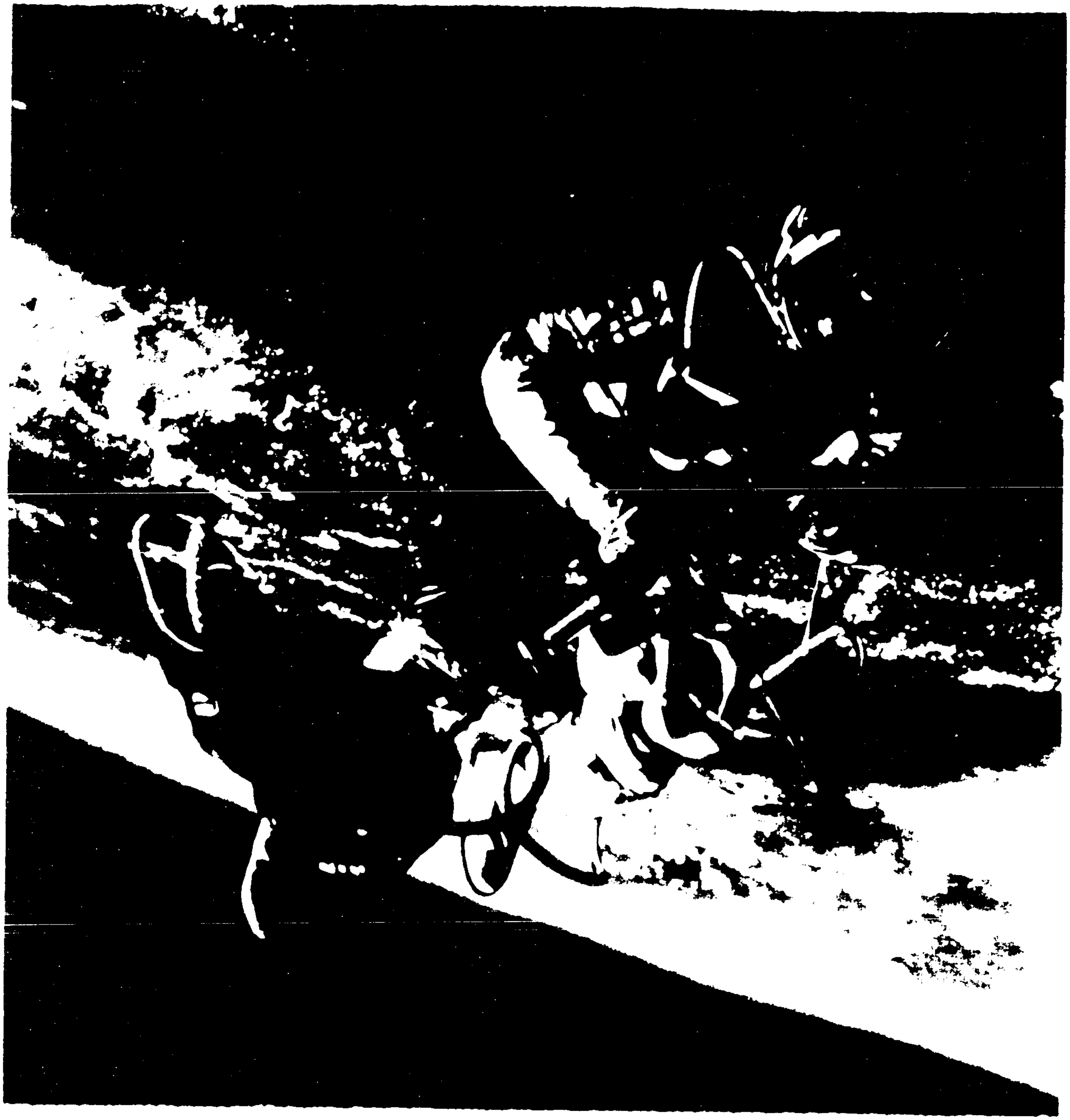

Figure 1. Astronaut Edward White II, Floating Freely in Space During the Space Walk From the "Gemini-4".

I. WEIGHTLESSNESS AS A SPECIFIC CONDITION AND EXTREME SPACE FLIGHT FACTOR /7

1. The Significance of the Gravitational Forces in the Regulation of the Constancy of the Internal Environment of the Organism

The opinion is generally accepted that life arose under conditions in which the effect of the Earth's gravitation was constant. Organisms of all vertebrates including man consist primarily of cells, intracellular fluid and solid substances. Since the influence of gravitational forces on these structures differs, achievement of physiological homeostasis arose in the course of evolution by the establishment of certain relationships between the principal components of the body. Constancy of the internal environment of the organism, to a large extent, depended upon the ability of supporting structures to counteract the force of gravitation [263].

In the course of evolution life probably passed through three stages. It appeared in an aqueous medium, then propagated in the atmosphere and on the surface of the land. The influence of weight on the regulation of vital processes in organisms living in an aqueous medium and on dry land is different.

Inasmuch as the organism of animals that live a terrestrial form of life consists of structures with different densities, the external forces tend to change their shape until they are counteracted by other forces. The stresses that arise under these conditions vary at different points on the body and in the final analysis are transmitted to the skeleton. As the weight load on the /8
skeleton increases, its strength must increase as well. However, as far back as 1638 Galileo noticed that if the weight of a body that has a cubic shape in the simplest case increases in proportion to its volume (or the cube of the linear dimension), the ability to withstand this weight will increase only in proportion to the area of the cross section (or the square of the linear dimension [277]). Therefore, in large land animals the ratio between the mass of the skeleton and the mass of the body is greater than in small ones. Prolonged action of g-forces on a centrifuge increases this ratio in experimental animals and also leads to the development of other morphological and functional changes [214, 277]. However, the resistance to a change in weight has been found to be a function of the mass of the body [161].

It is interesting that in the case of mammals which in the course of evolution have returned to life in an aqueous medium, the relative weight of the skeleton (in percent of body weight) is less than in terrestrial mammals. This probably has to do with the lower magnitude of the weight load on the supporting structures under conditions of immersion in water. Similar conditions have been observed in these animals as far as the relative weight of the marrow is concerned, which is an important focus of the hemoglobin synthesis [68].

Counteracting the force of gravity is accomplished not only by the strength and the functional organization of the skeleton, but also by the active participation of the skeletal musculature. The formative influence of terrestrial gravitation on the bone and muscle system is particularly evident in the process of evolution of terrestrial organisms, and they have acquired /9 the ability to maintain their posture and move about in space, overcoming the effects of gravitation. Water organisms that are placed on dry land, as a rule, do not have this ability, since in the environment to which they are accustomed there is practically no direct need for overcoming the force of gravity, if we do not consider the problems that are associated with the external pressure on the body. In other words, a living organism can function satisfactorily only under certain conditions of weight stress, determined primarily by the characteristics of its support and motor apparatus.

The influence of the force of gravity also makes itself felt in the characteristics of the distribution of the fluid medium in terrestrial organisms, which has to do with the presence of hydrostatic pressure of the fluid or, in other words, with its weight. Figure 2 shows various levels of blood pressure in different parts of the arterial vascular tree under different gravitational conditions, according to the laws of hydrostatics. The changes in the distribution of the blood which occur under the influence of gravitational forces and accelerations affect not only the circulation of the blood but the function of the lungs as well [276]. We know for example that due to the considerable difference between the specific gravities of blood and air, which are on opposite sides of a thin, delicate alveolar membrane, the lungs are damaged under the influence of g-forces before other organs are.

Adjustment to hydrostatic redistribution of the blood in terrestrial animals is provided by neural and hormonal regulation mechanisms. In the case /10 of man, who has a vertical orientation with respect to the ground, the significance of these accommodative mechanisms are particularly great.

The force of gravity also governs the regulation of the internal environment of the organism, as well as its growth, shape, energetic structure, orientation and behavior. Specific examples of this dependence can be seen in the phenomena of geotropism in plants or the postural reactions of vegetative and somatic functions in animals. There is also a possibility of a primary influence of gravitation on the cellular and subcellular structures, particularly the distribution of the nuclei and mitochondria in the cells [244].

The mechanical effects of the action of the force of gravity on the supporting structures and the distribution of fluid in the living organism stimulate a complex of response reactions that ensure its "balance" with respect to the environment. An ability which is specific to biological objects, namely, to adjust actively to external conditions and reflect them in the characteristics of their own structure and function, is provided by participation of various receptor structures and the conditioning effects of the central nervous system.

The functions of the central nervous system, taking neuromuscular and sensory reactions into account, on moderate changes in gravitation are plastic and adaptive to a large degree. Neuromuscular reactions usually depend on the position of the body relative to the direction of the force of gravity. Ontogenetically, animals and man are accustomed to assuming and holding a position and orienting the body by means of kinesthetic, visual, vestibular and statokinetic information. The interpretation of such signals and the response reactions to them involve the development of a response sensomotor program which depends upon gravitation. The proprioceptive system includes, in particular, mechanoreceptors located in various parts of the body which normally are structured and calibrated on the basis of terrestrial ratios between mass and weight, as well as the vestibular apparatus, which is very sensitive to acceleration and gravitation, particularly the otolith part. The latter plays an important role in the regulation of the sensomotor activity and in some cases transforms or blocks afferentation from other sense organs, including visual ones. However, when the vestibular information is excluded, the level of visual afferentation may increase and become independent of the gravitational background. This process, it turns out, is improved by experience, learning, etc., and is consciously controlled. Inasmuch as the individual adjusts to a wider range of sensations as a function of learning new habits, the actual effect of the existing gravitational conditions serves as a useful method of training cosmonauts for flights in space and to the moon [244]. /11

The force of gravity is a factor which has a significant influence on the regulation of the internal environment of the organism, so that there is sufficient basis to expect the development of a number of functional and morphological changes under conditions of weightlessness. Although certain forms of animals have adjusted well from the physiological standpoint to life in water, on dry land and in the air, in the course of evolution living organisms have not encountered prolonged effects of true weightlessness. /12 Therefore they have not developed any kind of specific mechanisms for compensation for the consequences that arise from absence of weight, if such mechanisms are in fact possible [30]. In the most general form, these consequences boil down to the development of the phenomena of "disuse" or "atrophy from inaction". The absence of gravitational stimuli causes changes in the autoregulation of the entire organism, which are aimed at establishing adequate interactions with a number of reduced requirements from the environment. From this standpoint, the essence of the changes that occur can rightly be considered as a manifestation of the adaptation process. However, this kind of adaptation is accompanied by a narrowing of the functional capacities of the organism and its resistance with respect to gravitational and other external influences. If we assume that mankind theoretically is capable not only of adapting but adjusting to weightlessness on a homeostatic basis, in the final analysis this will lead to genetic changes, including those that are fundamental. New properties of the bone and muscle, cardiovascular, endocrine and central nervous systems will arise. In a number of generations that are constantly subjected to the affects of weightlessness, the establishment of a new level of homeostatic equilibrium could theoretically be promoted by the mechanism of natural selection.

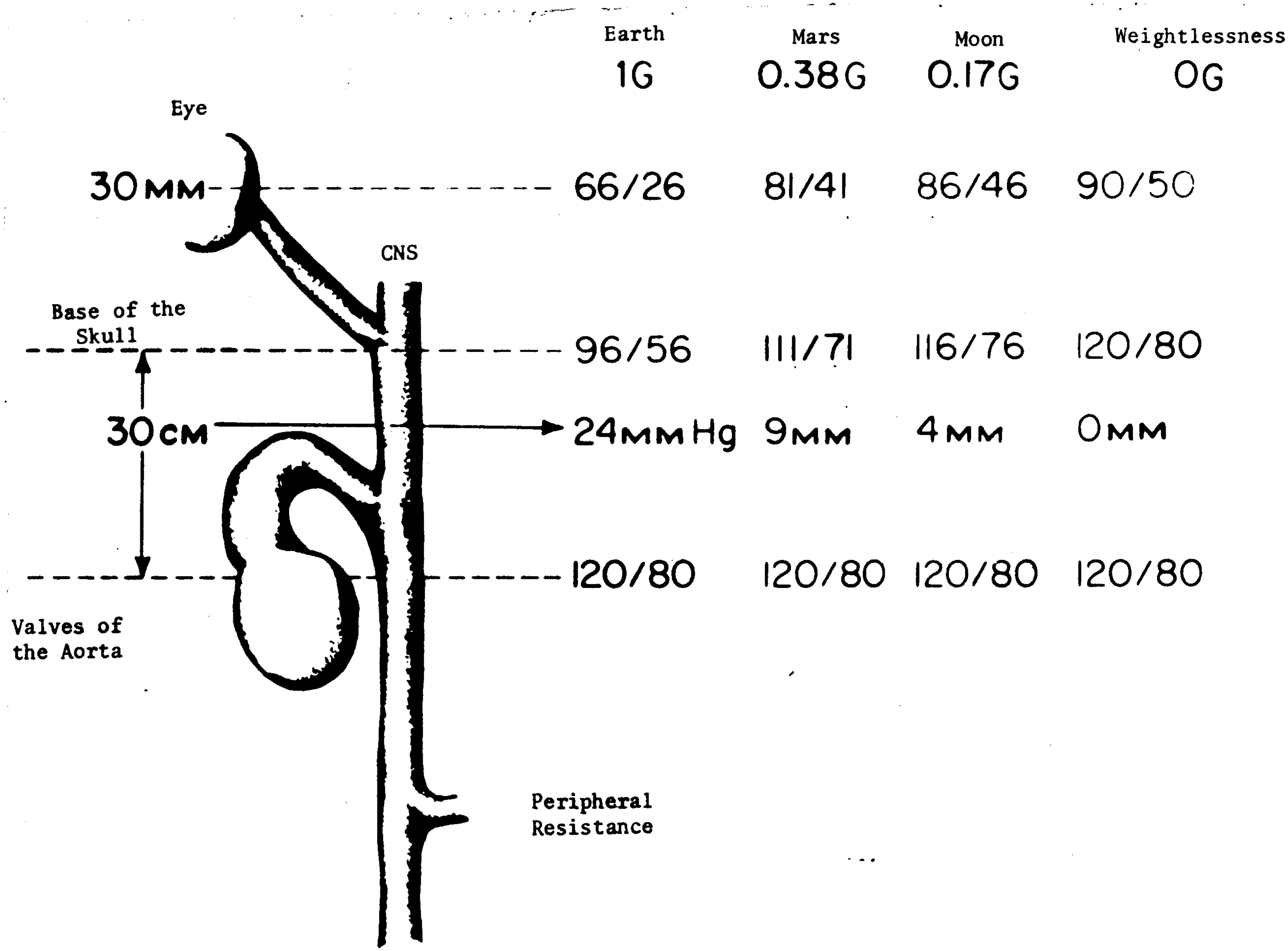

Figure 2. Levels of Systolic and Diastolic Blood Pressure in Man and Their Changes at Various Levels of Reduced Weight (According to Armstrong, Haber and Strughold [137]).

2. Basic Approaches to the Study of the Influence of Weightlessness on the Human Organism /13

Such unusual space flight factors as subgravitation and weightlessness have been the subject of many theoretical and experimental studies. Even in the early works of K. E. Tsiolkovskiy (1883, 1895, 1911) there are descriptions of specific conditions which man could expect in space: lack of weight or sensations of pressure on surrounding objects, the possibility of holding any mass in the hands without feeling its weight, lack of such concepts as "up" and "down". Tsiolkovskiy also predicted a change or a loss in spatial orientation and a deterioration of the sensomotor function under space conditions, changes affecting the distribution of the blood and the development of anatomical changes in the human organism. Although Tsiolkovskiy felt that man would be able to adjust finally to conditions of weightlessness, he proposed rotating the spacecraft to create artificial gravitation [117]. Later Hermann Oberth studied the influence of weightlessness on man in the course of interplanetary voyages. "If a prolonged state of weightlessness leads to unexpected consequences, which seems doubtful however," wrote Oberth, "then it will be necessary to connect two spacecraft by a cable several kilometers long and rotate one relative to the other."[241]. He recognized the possibility of an unfavorable influence of the Coriolis forces that arise in rotating craft with artificial gravitation.

The first experimental studies of the influence of weightlessness on the /14 organism of mammals were conducted during the flights of rockets that took place simultaneously in the USA and the USSR following World War II. Scientists in both countries monitored the condition of various physiological and behavioral functions in small animals, especially studying the frequency of cardiac contractions and respiration, blood pressure, body temperature, sensory and motor activity, as well as reflex reactions and behavior, caused by the participation of the central nervous system, and other functions under changing accelerations and short term states of zero G. Although some animals died because of failures in the technical apparatus, the results obtained in those animals that returned to Earth showed that stress associated with flight aboard a rocket, including periods of weightlessness, did not exceed the limits of biological resistance of the mammalian organism [122, 139, 204, 225, 265]. This view was later confirmed by more extensive studies and experiments that were performed aboard orbiting spacecraft [28, 89, 123, 135, 193, 278].

Brief periods of weightlessness were also produced aboard aircraft flying along a Keplerin trajectory [201]. These "parabolic flights" were involved primarily with a study of the sensory, motor and vegetative reactions in animals and man, as well as the condition of the higher nervous activity. The results of these studies showed that when certain measures are taken to prevent the action of weightlessness lasting several seconds to one minute, no harmful effects occur involving the functional condition and working ability of man and /15 that consequently he may be exposed without harm to the action of weightlessness of this duration during space flight [65, 119, 140, 184, 223].

Suborbital and orbital flights by cosmonauts opened up a new chapter in space biology and medicine. As the lengths of the flights gradually increased from several minutes to several weeks, extensive medical and biological studies were carried out both in space and on the ground [25, 105, 153, 197, 200]. They included preflight and postflight functional tests and examinations of the cosmonauts, medical observations during flight, telemetric recording of physiological and psychological functions and monitoring of environmental parameters in spacecraft. The astronauts and cosmonauts, including doctors, took part in these studies both as subjects and as experimenters [22, 58, 87, 106, 107, 152].

The study of those factors that characterize the health and working capacity of cosmonauts under the prolonged influence of weightlessness were of the greatest interest. These included the following:

- the state of the vitally important functions, disposition to illness, resistance to stress effects during flight and afterward;

- simple and complex motor reactions, coordination of movement, the possibility of carrying out work operations, including those in critical situations, the ability to perform scientific observations and evaluate their /16
results in flight;

- the adaptability of spacecraft for life, work and rest of cosmonauts in a state of weightlessness.

The information gained in the course of these studies was used to improve the selection and training of cosmonauts, to improve the design of the spacecraft themselves and also to work out means of preventing the unfavorable influence of prolonged weightlessness on the human organism.

Inasmuch as true weightlessness only develops under flight conditions that are associated with the execution of a great many working operations and consequently are only slightly suited for systematic investigation, various types of laboratory models were worked out. The latter include water immersion, systems for holding individual parts of the body in a suspended state, pneumatic supports and other methods of reducing friction, prolonged stays in a horizontal position, as well as various methods of sensory deprivation [32, 48, 97, 160, 175, 185, 192, 272, 277]. In studies involving complete submersion in water lasting up to seven days and remaining in bed for periods up to 120 days, reactions to simulated weightlessness were studied in terms of their effects on the antigravitational structures of the organism, the intravascular hydrostatic pressure, metabolism, water-salt exchange, functions of the cardiovascular and respiratory systems and other parameters [11, 39, 78, 93, 100, 194, 261, 266]. In the case of water immersion, regulation of
posture, methods of immobilization, possibility of performing work in space /17
using hand tools, and other types of activity were studied. The goal of the studies involving simulation of weightlessness consisted in clarifying the nature of the undesirable reactions that occur under these conditions and to work out the principles, methods and means of preventing them on a long term

basis. In particular, the studies involved evaluation of the effectiveness of such measures as cosmonaut selection, training and instruction, performance of physical exercise, standardization of food ration, as well as the use of medicinal preparations and substances that simulated hydrostatic pressure of blood. Other studies touched on the influence of hypokinesia on various structures and functions of the organism; on the cellular level, on muscle tissue and bone structures, processes of metabolism, water and fluid balance, resistance to infectious diseases, resistance to destructive processes and various stress factors [62, 63, 75, 98, 102, 103, 114, 125, 181, 220, 229].

Along with the accumulation of experimental data having a direct relationship to making manned space flights possible, a great many scientific problems of a more general nature were studied as well. They included the following: the theory of biodynamic and biogravitational reactions (i.e., reactions that are triggered by accelerations and gravitation) and systematic studies of biological problems associated with space flight [30, 88, 90, 188, 229];

- study of processes and mechanisms of loss of training, adaptation, homeostasis, and the biological rhythms in weightlessness [2, 43, 141, 149, 162, 182, 261]; /18

- study of specific reactions involving the sense organs and the interaction of analyzers [65, 67, 129, 144];

- determination of the state of the hormonal, immunological, regenerative functions and the blood system in weightlessness [1, 3, 5, 109, 146];

- the use of methods of mathematical simulation and statistical evaluation of data for purposes related to medical and psychological problems dealing with reduced weight and weightlessness [14, 27, 60, 87, 217].

The majority of medical and biological problems that develop in the early stages of space flights were solved by careful selection and practical utilization of the results of theoretical and experimental studies. The large body of information that has already been gathered in this area has been applied not only to the problem of keeping man in space but also to the daily needs of mankind.

3. The State of Reduced Weight (Subgravitation)

Moving about and working on the surface of the moon and other planets take place on the basis of such concrete manifestations of the laws of mechanics which differ significantly from the corresponding phenomena on Earth. Since the value of terrestrial gravitation (g_0) is a constant taken as 1, an acceleration which is less than g_0 will produce a state of reduced weight and will be 1/6 of this value on the moon. Accordingly, weight decreases on the lunar surface.

For the purpose of training cosmonauts for activity in such an environment, numerous theoretical studies and model experiments have been conducted. /19

The following were used as the critical parameters for conditions of lunar gravitation: oxygen consumption and carbon dioxide balance, diet and water exchange, working capacity, movement of the extremities and moving around, muscular and sensomotor activity. Problems not requiring moving around were performed with pressure in a space suit and without pressure. In model experiments in which the subject had firm support for only one hand, performing the task required 20% more oxygen than under terrestrial conditions [245, 248]. Applying pressure to the space suit considerably deteriorated the values of the various forms of human activity (Table 1). The energetics of locomotion at 1/6 G is a multifactor problem, one which is still being investigated [217, 251]. Such parameters as gait, force of adhesion to the support and the rate of motion of the extremities under terrestrial examination conditions were simulated with satisfactory approximation [259].

TABLE 1. INFLUENCE OF PRESSURE IN A SPACE SUIT UNDER CONDITIONS OF REDUCED WEIGHT ON VARIOUS FORMS OF MOTOR ACTIVITY IN MAN (ACCORDING TO HEWES [206])

Energy expenditure in locomotion in a space suit without pressure, kcal/hour

a.

Speed	Pressure	1/6 G	1 G	Bibliographical Sources Hewes [206]
Speed	3.2 km/hr	142	205	266
	6.4 km/hr	187	430	266
	6.4 km/hr on a surface sloping at an angle of 10°	329	709	137

b.

Gravitation	Excess Pressure in the Space Suit, mm Hg.	Maximum Speed of Forward Movement, m/sec.	Maximum Height of Jumping in the air, cm.	Long Distance Jump on the Horiz., cm.
1 G	0	3.44	52.0	164.0
	180	2.8	30.5	100.0
1/6 G	0	1.64	234.0	366.0
	180	1.22	140.0	214.0

One of the methods of simulation was used to reduce the force of adhesion to a support. As the level of simulated weight decreased a pronounced decrease in energy consumption was found [206, 248]. Figure 3 shows the relationship between energy consumption and gravitational forces and the rate of movement both in a space suit and in ordinary clothing [9].

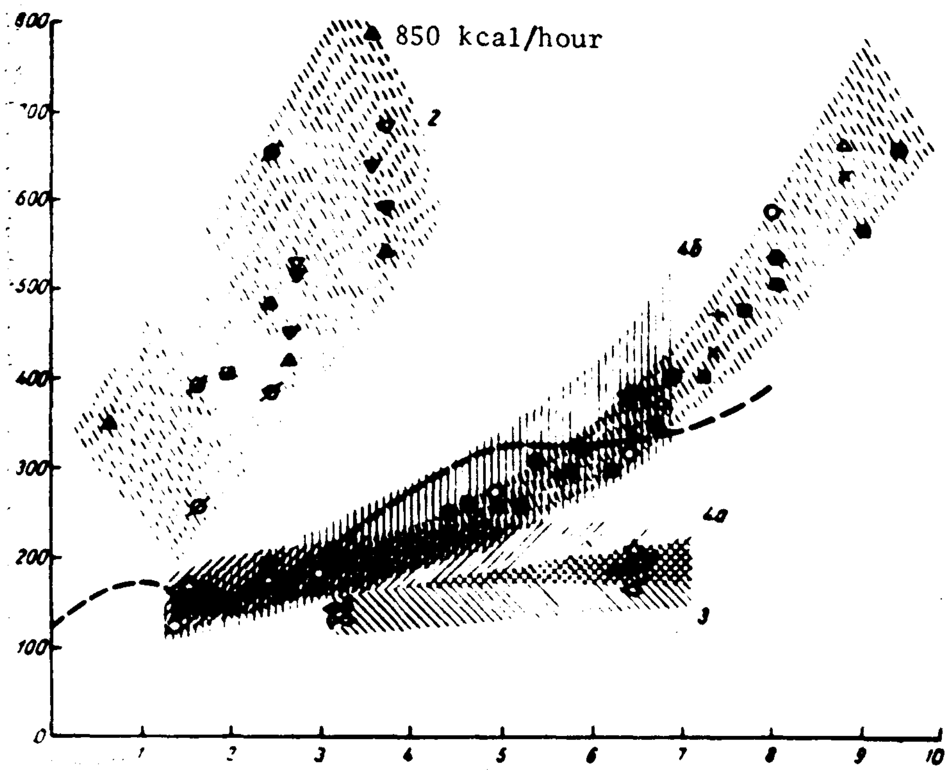

Figure 3. Influence of Lunar Gravitation and a Space Suit with Excess Pressure on Energy Expenditure While Walking on a Flat Surface. Shaded area: approximate regions of standard deviation. Abscissa: speed (km/hour); Ordinate: energy expenditure (kcal/hour).

Terrestrial gravitation
1. Ordinary clothing (according to Passmore and Dumin, 1965)
● Atzler and Herbst, 1927, 1928
△ Benedicht and Murschnauser, 1915
■ Brezina and Kolmer, 1912
✕ Douglas and Haldane, 1912
○ Margaria, 1938
✚ Morehouse and Miller, 1948 (according to Roth, 1966)
2. Space suit at ground level:
▲ Wortz (according to Roth 1966)
▼ Wortz et al., 1967
▼ Seminara and Shavelson, 1967
Ø Flexible space suit material or Rigid material (according to Robertson and Wortz, 1968)
At "altitude" in a pressure chamber:
▽ Wortz et al., 1967
▲ Seminara and Shavelson, 1967
■ Harrington et al., 1965
"Lunar" gravitation
3. Ordinary clothing, vertical suspension:
By the shoulders, Wortz and Prescott, 1966
On a universal joint. Wortz and Prescott, 1966, inclined suspension:
Flexible straps, Sanborn and Wortz, 1967
Straps with frame, Sanborn and Wortz, 1967
4. Space suit
Kuehnegger and Martell, 1967
— — Robertson and Wortz, 1968:
a. Vertical suspension by a frame
☆ Flexible space suit material
Rigid material
b. Inclined suspension:
★ soft space suit material
▼ Rigid material

The studies performed by NASA researchers at Langley on a simulator equipped with an inclined plane showed that as a result of a reduction in the force of adhesion, walking and running by human subjects were slowed approximately 40% in comparison with terrestrial conditions [206]. As the rate of movement increased, the inclination of the trunk forward increased to a greater degree under conditions of lunar gravitation [9, 206] in comparison with terrestrial (Figure 4). /20

On the whole, the subjects reported that their sensations and the magnitude of their efforts on the lunar simulator were the same as during brief parabolic flights under equivalent subgravitational conditions. On the basis of the studies that were performed, it was concluded that a cosmonaut dressed in a space suit that has been pressurized is theoretically capable of walking, running and working on the lunar surface provided that its surface is relatively solid and flat. It was also suggested that the researcher would be able to carry on his shoulders a load of up to 225 kg both when at rest and when moving around if the volume and resistance of the inflated space suit did not pose a significant obstacle [9, 224].

The first evaluation of the influence of actual lunar gravitation on man was obtained during the flights of the "Apollo" spacecraft [150, 151]. During the flight of "Apollo-14" two crew members (the commander of the craft and the pilot of the lunar module) spent about 34 hours on the moon, including nine hours resting from intensive physical work, while the pilot of the command module remained in orbit. Energy expenditure was 220-300 kcal/hour on the average. This value is approximately equivalent to walking under terrestrial conditions at a speed of 5 km/hour without using any kind of equipment or at the rate of 1 km/hour in a space suit. A comparison of postflight data from a medical examination showed that the physical condition of the command module /22 pilot, who was not subjected to the effects of 1/6 G, was worse than for the other two crew members (Table 2) [150]. He showed considerable weight loss, his orthostatic stability had decreased to a greater degree, the decrease in erythrocyte mass was more pronounced, his working capacity was lower, and the losses of total fluid volume were greater.

However, the results shown in Table 2 must be interpreted with great care. It is necessary to keep in mind such factors as the increase in water consumption on the part of the commander and the lunar module pilot during their stay on the moon and during the return flight. However, even with this in mind, the results of the Apollo-14 flight show that moderate work under conditions of reduced weight may have a positive effect.

On the other hand, the results of the Apollo-15 flight were the opposite of what was seen on the Apollo-14 flight. Two crew members, who worked on the lunar surface were found during postflight examinations to have a more pronounced decrease in their working capacity in comparison with the command module pilot. It is possible that the considerable increase in physical stress on the Apollo-15 crew on the surface of the moon neutralized the positive effect of the lunar gravitation. This dichotomy in the results of the two Apollo flights clearly shows that human working capacity at 1/6 G is subject to the influence of several parameters.

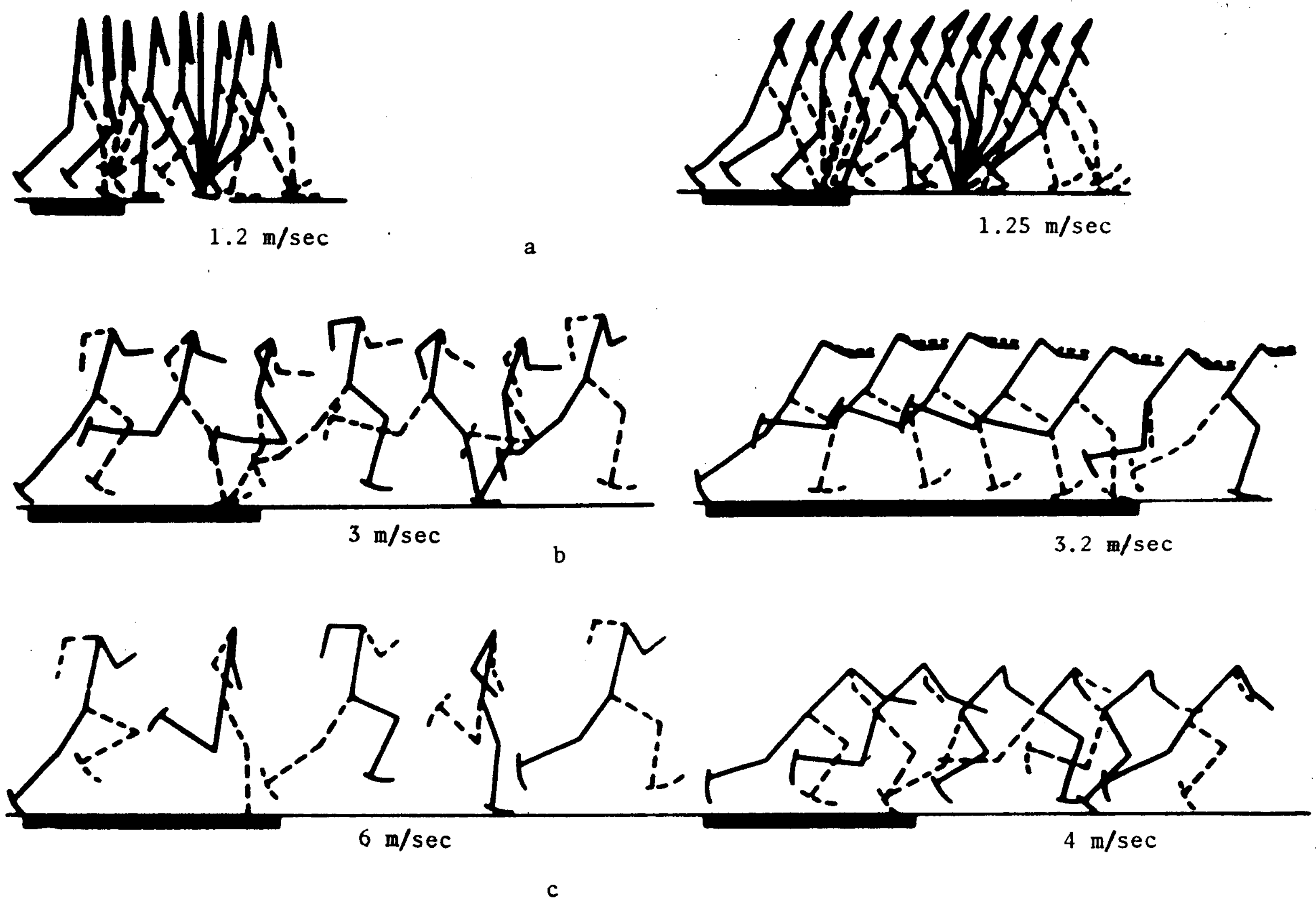

Figure 4. Change in the Kinematics of the Body During Locomotion Under Conditions of Lunar and Terrestrial Gravitation (After Spady) [9]. Heavy line -- length of stride; distance between figures 0.16 seconds; a, walking; b, running and jumping; c, running. I, terrestrial gravitation; II, lunar gravitation.

TABLE 2. COMPARISON OF PRE- AND POSTFLIGHT DATA FOR THE CREW MEMBERS OF THE APOLLO-14 SPACECRAFT, CONSTANTLY EXPOSED TO A STATE OF WEIGHTLESSNESS OR SUBJECTED TO THE EFFECTS OF 1/6 G [150]

Medical Data	Weightlessness	1/6 G	
	Pilot of the Command Module	Commander of the Craft	Pilot of the Lunar Module
Weight loss	- 5.4 kg	+ 0.45 kg	- 0.45 kg
Pulse rate (decrease in orthostatic stability)	Significant increase	Minimal changes	Minimal changes
Erythrocyte mass	- 9%	- 4%	- 2%
Plasma volume	- 10%	+ 1%	No change
Total fluid in the organism	- 18%	- 2%	- 2%
Intracellular fluic	- 27%	- 3%	- 3%
Working capacity (on the basis of data on oxygen consumption and systolic blood pressure)	Considerable decrease	No change	Slight decrease

4. Medical and Biological Effects of Weightlessness, Processes of Adaptation to Absence of Weight and Readaptation to Terrestrial Conditions /24

At the present time, considerable experimental data has been collected which characterizes the diverse phenomena of the processes involved in the adaptation of living organisms to the state of weightlessness and their readaptation to terrestrial conditions. Inasmuch as the references in this chapter constitute only a small part of those cited in the literature, additional information on this problem can be obtained in the surveys and thematic publications which have appeared previously [52, 88, 90, 107, 133, 153, 162, 225, 229, 248].

Even before the first studies were performed during space flights, it was felt that the effect of prolonged weightlessness could be the cause of a disruption of vitally important functions in the mammalian organism.

An analysis of the results of several hundreds of studies on the development of reactions caused by weightlessness shows that there are a great many changes involving the working capacity which impede the cosmonaut in his efforts to successfully cope with the state of weightlessness. However, it is the accommodative biological changes in the various systems of the organism, whose medical consequences are still not completely known, which are of primary importance. The data which we have at the present time contain a number of indications that there is an influence of weightlessness on the basic systems of the organism and its functions.

Table 3 summarizes some of the most general phenomena involved in the processes of adaptation to weightlessness and readaptation to terrestrial conditions. /25

Nervous system. The transition from 1 G to the state of zero G and the initial period of exposure to weightlessness are frequently associated with disturbances of spatial orientation, illusory sensations and symptoms of motion sickness, such as dizziness, nausea and vomiting. Symptoms of motion sickness arose as the result of disturbances to the functional interaction of the analyzers [67, 132]. Visual, auditory, tactile, defensive and taste sensitivity were usually normal. Psychic disturbances and hallucinations were absent. Sensomotor and indicative tests, caloric and other vestibular studies, the results of photographic investigations of the retina showed an absence of significant changes in comparison with preflight data [187]. However, the influence of weightlessness on the neuromuscular and sensomotor coordination also manifested themselves in changes in reflex excitability of the subjective perception of g-forces as well as a certain insufficiency of the motor function [124].

On the whole, as far as the function of the central nervous system, motor and neuromuscular coordination, diurnal periodicity of the organism and neuropsychological processes in cosmonauts were concerned, no important changes were observed during flight. Moving around was actually facilitated under conditions of weightlessness. Fortunately, there was no case of any disturbance of working ability associated with the dysfunction of the vestibular organ [144, 151].

Signs of neuro-emotional stress and an unpleasant state of fatigue that were noted by several cosmonauts may not have had a direct relationship to weightlessness and were due to other stresses in space flight. Generally /34
speaking, they were not reflected in the outcome of the space flight. In particular, this was obvious from the results of the "Apollo-13" flight which was successfully completed by the crew regardless of the extreme emotional stress involved.

Cardiovascular System. Although the condition of the cardiovascular system has been studied in animals and man during the initial experiments and prior to the lunar expedition, the picture still remains insufficiently clear. Cardiovascular changes occur as the result of the action of a great many variable factors including complicated interactions with other systems of the organism during weightlessness [60, 215]. The lack of training of the cardiovascular system is clearly demonstrated by the non-proportional speeding up of the pulse and respiration under the influence of accelerations during launching of the spacecraft and phenomena of orthostatic instability following return to

Earth. X-ray studies have revealed a decrease in heart size [153]. An analysis of the phase structure of the heart cycle, electrocardiographic indices and hemodynamic characteristics, in particular immediately following the end of the flight, clearly shows that the cardiac activity deteriorates temporarily to a certain extent [215]. It has been found that the longer the flight, the more severe the process of readaptation to normal gravitation will be. The general and physical condition both deteriorate, and the working capacity dropped to a level which resembles that seen following bed rest of corresponding length, or to an even greater extent.

The increase in pulmonary ventilation and oxygen consumption during the /35
post flight period are closely linked to distinctive phenomena associated with a lack of training. Soon after landing, even in a seated position, there was a significant increase in cardiac contractions which was not accompanied by an actual stress level. However, both the arterial pressure and the pulmonary function are not among the reliable criteria for the effects of weightlessness and more systematic studies in this area are required [4, 215]. For example, the establishment of differences in the condition of the cardiovascular system in the members of the crew that went to the surface of the moon and remained in lunar orbit on this same occasion introduced a certain degree of indeterminacy to the problem of the influence of weightlessness and subgravitation on the reactions of this system. Such an indeterminacy must be resolved by further studies [215].

Metabolism. Weightlessness affects the fluid balance as well as protein, fat, carbohydrate and mineral metabolism, and also affects certain endocrine functions [5, 24, 116, 148, 153]. The decrease in the mass of the body and consequently its weight has been observed following flights in practically all cosmonauts. Most of the weight deficit was associated with a loss of water (including intracellular fluid) and electrolytes, particularly potassium, sodium and chlorides. Thus, following the conclusion of the flights, a deficit in the total potassium content in the organism was observed. During the post-flight period, there was a retention of water and electrolytes which in most cases (but not all) allowed recovery of body weight within several days. The decrease in the erythrocyte mass observed by American authors following the end of flights probably was linked to the increased content of oxygen in the space- /36
craft atmosphere.

Bone-Muscle System. The weakening of the influence of external forces on the structures which support the weight load leads to a loss of calcium and other mineral substances that are important for maintaining the integrity of the bones [7, 203, 227]. If a loss of this kind is continued for a long period of time, the mass of bone and muscle and their resistance to stress will decrease. Although no muscle atrophy was observed in the cosmonauts following 14 days of exposure to weightlessness, there was a slight negative nitrogen balance and a slight weakness in the extremities [145].

Following exposure to weightlessness, Soviet scientists found changes in protein metabolism in animals and man [91, 107, 116]. The strength and tone of muscles as well as the perimeter of the lower extremities had decreased [81, 121].

TABLE 3. SEVERAL REACTIONS OF MAN AND ANIMALS TO THE EFFECTS OF WEIGHTLESSNESS*

Reactions	Conditions and Objects of Observations**	Sources in the Literature	Notes
1	2	3	4
Sensations of an unsupported position, floating, falling, spinning, turning, flow of blood to the head, deterioration of orientation in space, predominance of role of visual information in evaluating the position of the body in space.	Man (TW, KP, SF)	[16, 24, 25, 48, 65, 81, 107, 127, 132, 150, 151, 184, 186, 189, (189, 191, 199, 539)]	Emotional coloring of sensations (fear, joy, etc.) depends on the experience and training of the subjects. In orbital flight -- adaptation.
Displacement of successive visual image during g-forces -- downward (oculogravic illusion), and upward during weightlessness (oculoagravic illusion). Illusions are characteristic of the initial periods of a stay in weightlessness.	Man (KP, SF)	[25, 66, 186, 189, (204, 500, 522, 678)]	Actual position of visual landmarks during g-forces -- above the successive image, and below it during weightlessness. With fixation of the gaze on a landmark, the successive image coincides with it.
Slowing down of speed and accuracy of movements; errors in trying to hit the center of a target (deviation of hits upward).	Man (KP, SF)	[16, 24, 25, 84, 107, 186 (22, 42, 206, 334)]	Only in the initial phase of SF, then adaptation.
Deterioration of the ability to carry out measured muscular efforts and to evaluate the differences in mass of objects not fastened down.	Man (KP)	[127, 189, (495)]	

TABLE 3 (Continued)

Reactions	Conditions and Objects of Observations**	Sources in the Literature	Notes
1	2	3	4
Changes in postural, oculomotor reflexes and behavior.	Animals (TW, KP)	[131, 186, (22, 67, 192, 285, 291, 344)]	Changes less in delabyrinthized animals than in normal ones.
Decrease in oculomotor activity, asymmetry of nystagmoid movements.	Man (SF)	[107, (7, 193)]	
Development of pain during movement or individual symptoms of it (dizziness, discomfort in the stomach, nausea, vomiting, etc.)	Man (KP, SF)	[21, 22, 26, 65, 67, 81, 127, 129, 132, 148, 153, 183, 186, (189, 383)]	Participation of both vestibular and extralabyrinthic mechanisms suggested, as well as a change in the interaction of afferent systems.
Frequency of respiration and pulmonary ventilation: increase during flight along the KP; various changes in the SF; increase in the postflight period.	Man (KP, SF, R)	[16, 23, 29, 58, 106, (22, 23, 191, 198, 542)]	Changes in flight depend on previous action of g-forces or the nature of the work.
Gas exchange: increase during flight along a KP; decrease (according to the data from analysis of regenerative substance) during the SF; increase during the postflight period.	Man (KP, SF, R)	[16, 23, 26, 29, 58, 61, 143, 153]	On the basis of an analysis of samples of expired air, collected during the SF, both a decrease and an increase were noted. A decrease in the PBR.
Decrease in consumption of food.	Man (SF)	[25, 107, 148, 153]	Not observed on all flights. Characteristic of PBR.

TABLE 3 (Continued)

Reactions	Conditions and Objects of Observations**	Sources in the Literature	Notes
1	2	3	4
Pulse frequency: slowing of normalization following action of g-forces; subsequently, a tendency toward slowing, increase in variability (possible arrhythmias of the bigeminal type); in the final stage of long SF, slight increase.	Man, animals (SF)	[4, 14, 25, 28, 54, 57, 106, 107, 147, 153, 173, (22, 23, 189, 191, 441, 613)]	With PBR following initial decrease in frequency of pulse, increase in frequency (lack of training).
Arterial pressure: moderate decrease, followed by stabilization, tendency toward a decrease in pulse pressure.	Man (SF)	[5, 22, 23, 30, 57, 58, 59, 147 (279)]	In the PBR, initial decrease followed by an increase (sympathetic effect).
Heart: decrease in size (according to data from X-ray studies); symptoms of a decrease in the contractile ability (according to the data of electrocardiographic and seismocardiographic data and the results of a phase analysis of the cardiac cycle).	Man (SF, R)	[23, 87, 107, 153, 215, 274]	Descriptions of cases of an increase in the mechanical activity of the heart during flight.
Bone tissue: demineralization (according to the data from X-ray photometry) due to loss of Ca^{++}.	Man, animals (R)	[7, 25, 91, 147, 148, 151, 153, 203, (199, 401)]	No changes observed when using the method of photon absorption.

TABLE 3 (Continued)

Reactions	Conditions and Objects of Observations**	Sources in the Literature	Notes
1	2	3	4
Muscles: decrease in volume and strength.	Man, animals (SF, R)	[23, 25, 101, 121, 153, 184]	Primarily atrophy of the anti-gravitational musculature.
Dehydration (decrease in plasma volume, followed by loss of intracellular fluid)	Man, animals (R)	[25, 91, 145, 148, 150, 151, 215]	Decrease in plasma volume develops on the first or second day (Henry-Gauer reflex). Recovery possible later.
Decrease in weight (mass) of the body by 2-5% of the original value.	Man, animals (R)	[23, 24, 25, 81, 84, 151, 153, 187, 215]	Stay on the moon in individual cases decreased the weight loss of the body. Following the flight, the weight rapidly returned to normal (exception: 18-day flight of the "Soyuz-9").
Protein metabolism: increase in the urea content in the blood, increased excretion of the creatinine with the urine, negative nitrogen balance.	Man, animals (SF, R)	[5, 23, 29, 30, 91, 106, 107, 116, 145, 146, 187, 225]	Similar changes in the PBR.
Lipide metabolism: increase in the colesterol, lecithin and non-esterified fatty acid content of the blood.	Man, animals (SF, R)	[23, 29, 30, 91, 105, 106, 107, 187, 225, (191)]	Changes not constant, depending also on the nature of the diet.
Decrease in excretion of Na^+, Cl^-, K^+ electrolytes with the urine.	Man, animals (R)	[25, 91, 145, 146, 148, 150, 153]	Related to previous losses of electrolytes during weightlessness.

TABLE 3 (Continued)

Reactions	Conditions and Objects of Observations**	Sources in the Literature	Notes
1	2	3	4
Reduced excretion of 17--oxycorticosteroids in flight, increase in excretion following flight.	Man (SF, R)	[23, 81, 106, 107, 116, 146, 148, 153, 215]	Similar relationship in experiments with simulation of weightlessness.
Increase in concentration of antidiuretic hormone, aldosterone and renin.	Man (R)	[146, 148, 150, 215]	Increase in aldosterone noticed in SF as well.
Blood: neutrophilic leucocytosis, lymphopenia or lymphocytosis, eosinopenia, increase in ROE [?], changes in coagulatory and anticoagulatory systems of the blood; thrombocytes - decrease or absence of changes.	Man, animals (SF, R)	[3, 5, 23, 57, 81, 91, 105, 106, 107, 116, 148, 153, 187, 225]	Similar changes in experiments with PBR.
Delay in excretion of water from the organism in test with water load.	Man (R)	[5, 24, 25, 29]	Not noticed after 18-day flight of "Soyuz-9".
Deterioration of tolerance to transverse g-forces during the launching period.	Man (SF)	[13, 16, 107]	Not on all flights.
Sensation of heaviness of the body, rapid fatigue, difficulty in walking, muscular pains.	Man (R)	[25, 54, 81, 101, 107, 121]	Primarily after flights of long duration without preventive measures.

TABLE 3 (Continued)

Reactions	Conditions and Objects of Observations**	Sources in the Literature	Notes
1	2	3	4
Orthostatic instability.	Man (R)	[23, 25,29,55,105, 143,145,147,153,171, 225,(19,441,442)]	Develops also under conditions of terrestrial experiments involving simulation of weightlessness.
Decrease in physical working capacity.	Man (R)	[23, 54, 146, 148, 151, 153]	Consequence of hypodynamia.
Decrease in immunity.	Man, animals (R)	[1, 25, 91]	Increased danger of infectuous diseases during and after the flight.
Increase in duration of recovery period on long flights in comparison with short ones.	Man (R)	[25, 54, 81, 184]	Improvement in living conditions and use of preventive measures shortens the duration of the recovery period.

*In addition to data found in the bibliography (items without parentheses), the table also contains data from Gerathewohl and Ward [184] and data from Roth [248], (entries in parentheses).

**TW - Tower of weightlessness; KP - Keplerian parabola; SF - Space flight; R - readaptation period; PBR - Prolonged bed rest.

Changes involving physiological functions, occurring in a state of weightlessness, and their interactions are represented schematically in Figure 5. The directionality of individual changes (increase or decrease) was determined by comparing preflight and postflight data for the same crew members (represented in the diagram by small arrows that are located in the immediate vicinity of the indicated functions or component elements of the organism. The larger and longer arrows, which join the various parts of the diagram, were used to represent the possible relationships between the changes in individual functions and systems with others) [274].

Regardless of the fact that prolonged weightlessness and a decrease in stress can have asthenizing effects on the bone and muscle system, there is no need to view this as a barrier to long space flights which are planned for the future. In the first place, in order to maintain the health and uninjured status of the organism, it may be found to be effective to use a number of protective measures such as physical exercises during flight, preflight training, a special diet, medicinal preparations, artificial gravitation and other measures. In the second place, some of the symptoms of insufficiency which are observed following space flight may be due not so much to the influence of weightlessness itself as to other factors and stressful influences that are associated with specific conditions of these flights. Although the rate and limits of the changes caused by weightlessness in the organism have not yet been determined completely, it is known that man can adjust to these conditions at the price of certain physiological losses. /37

We know from examination data that the most important factor in studying weightlessness is the determination of the accommodative changes, the level of adaptation and the measures that are necessary for its retention. There is an indication that man can live and work at zero G for several weeks and that certain adaptive processes occur in the course of the establishment of homeostasis at a new level.

The schematic representation of the hypothetical concepts that refer to the various most significant adaptational processes is shown in Table 4 [150]. Essentially, it is assumed that the total volume of blood circulating in the organism is redistributed in accordance with a new field of forces that arises during weightlessness. This factor includes the influence of hormonal reactions which restore the disturbed physiological equilibrium. The activity of the heart, respiration, metabolism are all changed, so that they can adjust to the reduced physical stress on the organism. The assumption appears justified that all functions may possibly be stabilized at a new lower level of activity. The schematic diagram of the sequence of these processes is found in Figure 6 [151]. /38

The second big problem is developing methods of protecting the organism against the unfavorable effects of weightlessness. Insufficiency of the bone-muscle system and the lack of training of the cardiovascular system may be viewed as dangerous symptoms. Work aimed at finding methods of protection have included experiments on animals and research with human participation. It was recently reported that animals can be trained so as to be able to perceive an increased level of G as a physiologically tolerable, or normal,

and that gravitation, as a stimulus, can influence the behavior of mammals [231]. The minimal force of attraction at which motor functions and bioelectrical potentials of muscle return to normal is about 0.3 G [130]. However it must be kept in mind that the problem of the need for artificial gravitation for man in space is a very complicated one and requires further study. The advantages and limitations of this method must be carefully weighed, particularly with consideration of the function of the vestibular apparatus /39
[31]. It is necessary to study the preventative and therapeutic measures which must be carried out before man makes the transition to a state of altered gravitation and during the period following.

TABLE 4. LIST OF EXISTING HYPOTHESES WITH RESPECT TO PROCESSES THAT INFLUENCE THE ADAPTATION OF MAN TO WEIGHTLESSNESS [150]

Phenomena	Reactions of the Organism
Influence of weightlessness. Redistribution of the volume of circulating blood.	The organism attempts to reduce the volume. There is a decrease in the content of antidiuretic hormone and production of aldosterone.
Losses of water, sodium and potassium (loss of body weight).	Decrease in plasma volume. Increase in aldosterone content (secondary aldosteronism).
Increase in sodium retention. Loss of potassium continues. Acidosis in the cells, alkalosis in the intercellular fluid.	Intercellular exchange of potassium and hydrogen ions. Decrease in bone density, potassium retention in muscle cells, as well as muscle mass, possibly including cardiac muscle.
Respiratory and renal compensation. Weight loss ceases.	Stabilization at a new effective level for the volume of circulating blood. New fluid and electrolyte balance in the organism established.

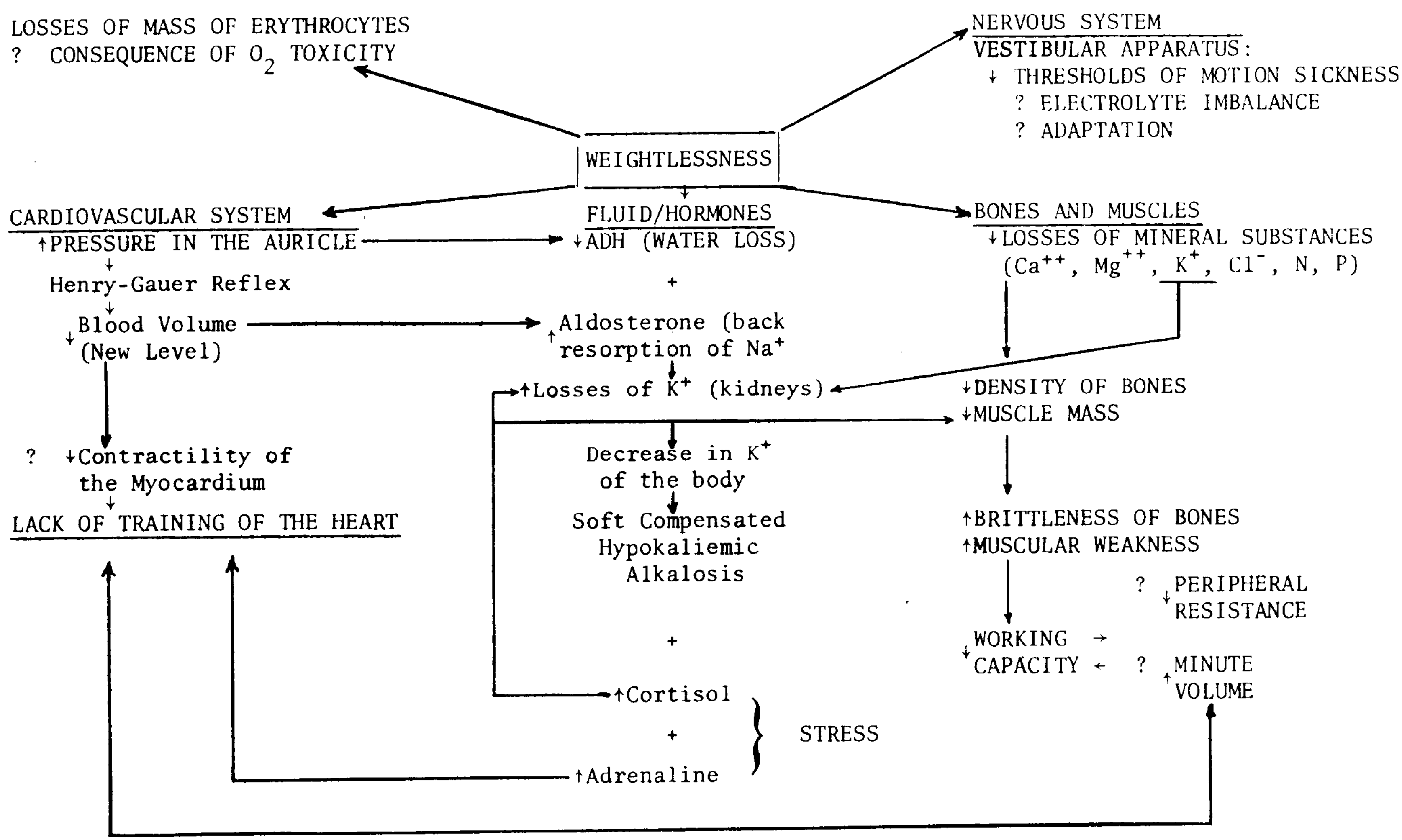

Figure 5. Some Effects of the Influence of Weightlessness on Man Adopted Working Hypothesis (S. C. White, C. Al Berry, R. R. Hassberg) [274]

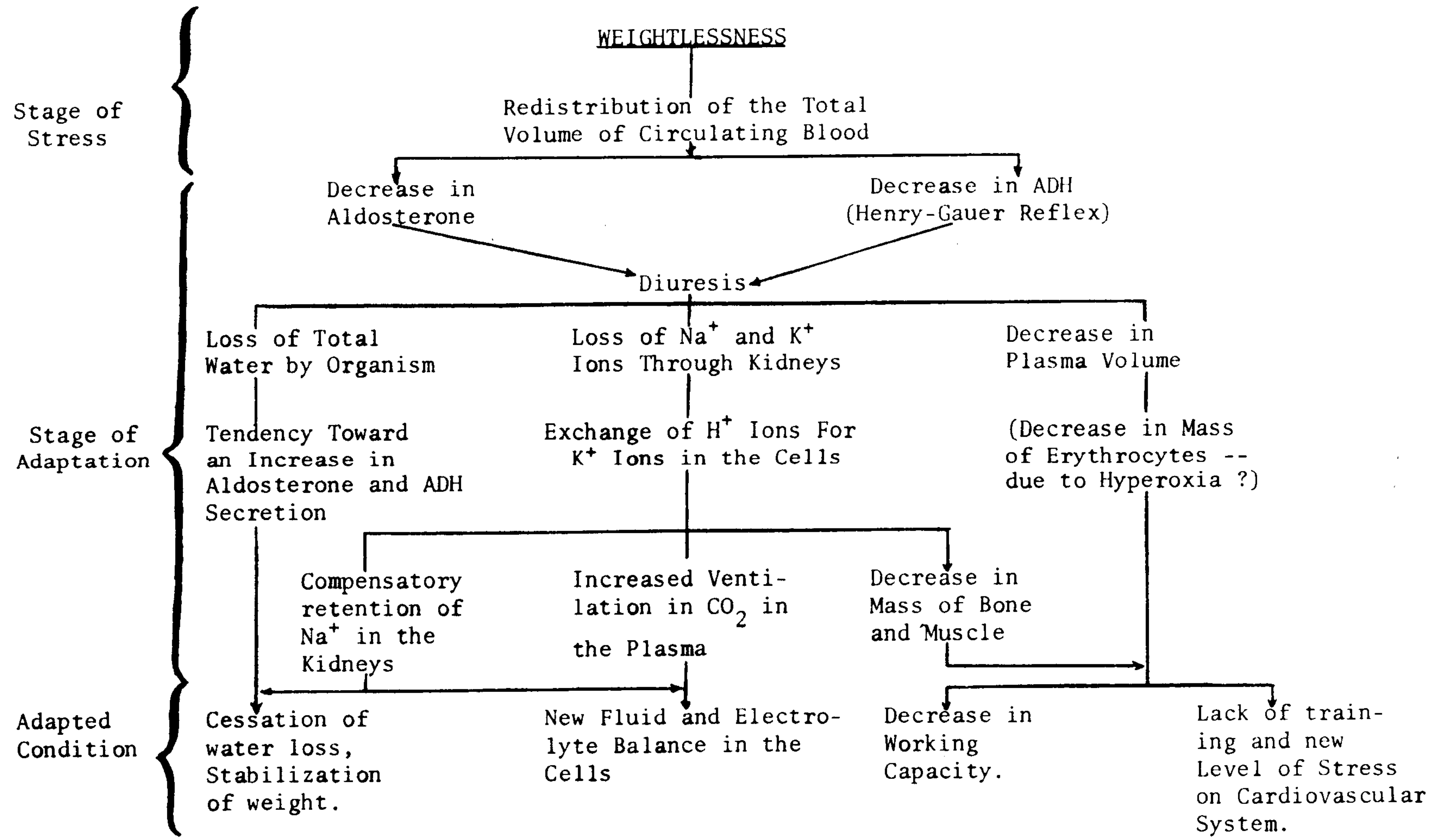

Figure 6. Diagram of Proposed Process of Adaptation to Weightlessness (According to Leach, Alexander, Fischer, 1970) [151].

II. MECHANISMS OF FUNCTIONAL CHANGES IN THE CONDITION OF WEIGHTLESSNESS AND IN ITS SIMULATION UNDER LABORATORY CONDITIONS /40

1. Reactions That Are Primarily Responsible for the Changes Involving the Afferent Branch of the Nervous System

Although experiments on animals and observations of human beings during parabolic and space flights have revealed certain changes in the organism under the influence of weightlessness, the majority of such processes as psychomotor activity, motor activity, and the functions of the central nervous system, the interactions between the crew members and their professional habits remain unchanged. A detailed study of the subjective sensations and sensomotor reactions that arise in human beings during flights in a Kepler trajectory can be found in previously published papers [65, 127, 183, 188, 248]. We also have data on the various forms of activity inside and outside the spacecraft during weightlessness, as well as its simulation, for example, with respect to putting on clothing, using handles, switches and manual tools, carrying out work in orbit and on the moon, techniques and methods of moving around, dynamics of turning at will, methods of limiting speed and braking, as well as methods of moving around in space and on the moon [71, 90, 248, 253]. Although the functions of the vestibular analyzer are of interest in themselves, we must also consider the mechanisms of cerebral control and the significance of contradictory nerve influences.

Many researchers have shown that during the transition from terrestrial gravity to a state of weightlessness, some persons show an increase in the predisposition to motion sickness [65, 67, 129, 142, 183]. It has been found that unfavorable reactions during orbital flights may be caused both by a lack of gravitational stimulation of otoliths and by a possible stimulation of the semicircular canals during movements of the head and body [128]. In weightlessness, the otolith organs react to changes in acceleration [188]. Following an initial increase in activity during the transitional period, they adapt to zero acceleration and their bioelectrical activity decreases [200]. Observations made during parabolic flights have shown that the development of such reactions as nausea and vomiting are governed by the function of the labyrinth [198]. Reactions to Coriolis acceleration usually develop in persons with a normal labyrinth and do not occur in persons having a labyrinth that is defective [165]. The illusion of "spinning" also develops in individuals with a normally functioning labyrinth [176]. /41

Table 5 describes some of the illusory sensations and symptoms of motion sickness that arise in astronauts aboard Apollo spacecraft [152]. It is clear from the table that almost all the astronauts who flew aboard the Apollo spacecraft mentioned cases of motion sickness in their anamnesis that developed aboard ground, air and water means of transportation. Four individuals never had suffered motion sickness and only three out of 27 vomited in space (not necessarily as a result of the action of weightlessness). In other words, the relationship between the existence of motion sickness in the anamnesis and the development of symptoms of this disease during space flight is quite unclear. Unpleasant sensations were likewise suffered by the Soviet /45

MANIFESTED BY THE ASTRONAUTS ABOARD THE APOLLO SPACECRAFT

Flight	Astronaut	Flying time in aircraft prior to space flight (in hrs)	Development of Motion Sickness In The Anamnesis			Symptoms of Illusory Sensations and Motion Sickness During Space Flight			
			Aboard ground, Air and water means of transport	During Flight on a Parabola to simulate weightlessness	During Rolling of the capsule at sea and training for crashes	Illusion of Spinning	Unpleasant Sensations in the Stomach	Nausea	Vomiting
	A	4,517	x						
7	B*	4,107	x	x	x				
	C*	3,574	x		x	x			
	D	5,627	x				x	x	x**
8	E	4,358	x	x	x		x	x	
	F*	3,399	x	x			x		
	G	4,323							
9	H	4,266			x	x	x		
	I	2,279	x	x	x		x	x	x
	J	5,221	x						
10	K	4,747	x						
	L	2,787	x				x		
	M	6,400	x	x	x				
11	N	4,425	x	x	x				
	O	3,676	x	x					
	P	4,057	x						
12	Q*	3,638			x				
	R	3,914							
	S (E)	4,282	x	x	x				
13	T*	6,249					x	x	x
	U*	6,135					x		
	V	5,063	x						
14	W*	3,594	x						
	X*	4,276							
	Y (H)	4,780			x				
15	Z*	6,715		x		x	x		
	AA*	3,370							

* Did not participate in flights previously
** Related to sickness.

cosmonauts. It is possible that this was caused by the fact that with a lack of gravitation the unusual afferent signals created a false sensation of tilting and falling, and consequently a feeling of discomfort in the stomach, dizziness and fatigue. Hydromechanical processes in the semicircular canals can also promote the development of spatial illusions, especially the feeling of spinning and the idea that the body is upside down [176, 252].

The vestibular function is linked in different ways to the functioning of other systems in the organism. We know that prolonged immobilization and a stay in weightlessness produce serious effects in circulation [4, 43, 87, 264]. Under weightlessness conditions, there is sometimes a predominance of the influence of the vagus nerve which is expressed in the form of bradycardia and gastrointestinal disturbances, may cause nausea and the sensation of discomfort; these phenomena may easily be taken in error as vegetative symptoms of sickness having a vestibular origin. Such symptoms may be due solely to insufficiency of the cardiovascular system as the result of the fact that a sensation of danger arises from an inadequate perception of the inertial and dynamic external conditions, a need for muscular exercise, resulting in a diversion of the circulating blood to the muscles [254, 255]. As the duration of space flights increases and the influence of weightlessness acting on the afferent branch of the nervous system becomes more important, changes involving the receptors of the circulatory system and the neuromuscular apparatus may considerably alter the internal condition of the organism. Under certain conditions, this causes functional disturbances. The origin of these dis- /46
turbances probably can be traced by returning to the primary sources or to a synergistic interaction of the latter. The primary sources include the following: decreased activity of the neurohumoral and neuro-reflex mechanisms of regulation as a result of a lack or limitation of sensory input, disturbance of the neuro-physiological reactions caused by inadequacy or an unusual nature of sensory input, as well as an insufficiency or interruption of neurophysiological functions as the result of g-forces or a conflict between individual systems.

In conjunction with the action of prolonged weightlessness, there are two basic problems that arise: 1) to what degree will the sensory perception and motor reaction change and 2) will the changes in the functional condition of the organism be so great that subsequent readaptation to conditions of normal gravitation will be difficult and even dangerous? Essentially this boils down to the question of whether we want the organism to adapt completely to weightlessness conditions. In order to answer these questions it is necessary first of all to examine the complicated processes of neuro-physiological adaptation in greater detail and in the second place to determine the nature of the compensatory possibilities of the organism. At the present time, we have sufficient data that we can predict the reactions of the organism of mammals to a stay in weightlessness for a relatively short time. However, these data do not make it possible to draw any specific conclusions relative to the prevention of problems involving the afferent branch of the nervous system, and the related illusory sensations and attacks of motion sickness that accompany it and finally, with respect to the desirability of complete /47
adaptation by man to a state of weightlessness.

2. Reactions Which Are Primarily Caused By An Absence of Hydrostatic Blood Pressure

Redistribution of fluid in a system of elastic reservoirs is determined by the laws of hydrostatics. The hydrostatic pressure, whose level is proportional to the height of a column of fluid and its specific gravity, acting on the walls of the reservoir, causes their distension and corresponding movement of the fluid downward. This type of relationship also exists in the distribution of biological fluids (mainly blood) in man and animals under terrestrial conditions. Remaining in a vertical position is accompanied by deposition of a certain volume of blood in the lower half of the body, a decrease in venous return to the heart, systolic ejection and a number of corresponding compensatory reactions. Some feel that distribution of a fluid medium in the organism is the most important biological reaction to gravitation [196]. Walking, running, jumping, changing the position of the body in space all change the magnitude and direction of the gravitational shifting of the blood in man. Hence, our organism is in a state of constant readiness for carrying out compensatory reactions that are associated with the action of the hydrostatic factor. A constant stay in bed for a long period of time changes the magnitude and direction of the hydrostatic forces while immersion in water promotes their neutralization, since the immersion medium causes an equivalent counterpressure through the soft tissues on the vascular walls. In a state of /48
weightlessness the action of the hydrostatic pressure is completely eliminated. The result of all these processes is a relative redistribution of the blood from the lower half of the body to the upper half.

Hyperemia of the cutaneous coverings in man, the development of edema of the nasopharynx and tissues of the face under weightlessness conditions may also be linked to the mechanism of redistribution of the blood [25, 84, 143]. Electroplethysmographic studies, conducted during brief weightlessness in an aircraft, revealed an increase in the filling of the vessels and organs of the chest with blood [16, 82]. In an experiment aboard the American Biosatellite III, using a monkey [233] and also during water immersion of human beings [136], an increase was noted in the central venous pressure. A prolonged stay in a horizontal position has been found to cause stagnant dilation of the vessels of the fundus of the eye [45].

The relative increase in the central blood volume accompanying the decrease in hydrostatic pressure, according to the data of Gauer et al., is approximately 400 cm^3 [180]. It is an instantaneous reflex mechanism that leads to plasma loss and a decrease in the total volume of circulating blood to a level at which the filling of the central veins with blood corresponds to the "homeostatic norm". The receptor zone of this reflex consists of volume receptors which are located primarily in the region of the left auricle [179, 180, 205]. Impulses from the volume receptors, arising as a result of the distension of the left auricle, travel along the vagus to the medulla oblongata and the supraoptical region of the hypothalamus and inhibit the /49
secretion of antidiuretic hormone (ADH). The latter is stored in the neurohypophysis and is excreted from this organ into the blood. A decrease in the ADH concentration in the blood leads to a drop in the reabsorption of water and sodium in the kidneys, increased diuresis and plasma loss. At the same time,

there is a decrease in thirst and a negative water balance is established. Distention of the left auricle can also cause reflex spasm of the arterioles in the lesser circulation (Kitayev reflex) with a subsequent rise in pressure in the system of the pulmonary artery and an increase in the load on the right ventricle [64].

In experiments with laboratory simulation of weightlessness the plasma loss was 300-800 ml [220, 237, 268]. During the postflight period, the astronauts in most cases also showed a drop in the volume of circulating plasma by 100-500 ml (up to 13%) [146, 148].

The processes of restructuring of water-salt exchange in the development of a relative dehydration in the absence of hydrostatic pressure of the blood occur quite rapidly, primarily during the first 48 hours of exposure, after which the water exchange settles at a new lower balanced level [103, 268]. There is a decrease in the intensity of diuresis and the amount of water used [6].

The thickening of the blood caused by plasma loss is accompanied by an increase in the hematocrit [24, 156, 195, 256] and viscosity of the blood, although there may be a later decrease in the mass of erythrocytes [143, 237, 238]. As a result the ratio between the formed elements of the blood and the plasma returns to normal [195]. In the late stages of experimental simulation /50 of weightlessness there is a tendency toward an increase in the volume of circulating blood [95, 266]. Since no decrease in the volume of circulating plasma was observed following the 14-day flight of the "Gemini-7" spacecraft, it is necessary to assume the existence of some mechanisms for compensation for plasma loss. One of these may be related to the increase in the concentration of aldosterone during flight [143, 146]. This hormone, which is produced in the adrenal cortex as a rule promotes sodium and water retention in the organism. The question of the production of increased aldosterone excretion in the urine during space flight and its concrete causes require further research. We also cannot exclude the possibility that the restoration of the volume of circulating plasma against a background of a prolonged absence of hydrostatic pressure of the blood can also depend on the change in sensitivity of the volume receptors in the left auricle.

Fluid loss serves as one of the reasons for the decrease in body weight which frequently is recorded in the post flight period and following the end of experiments involving simulation of weightlessness [5, 24, 25, 103, 106, 107, 159, 190]. The magnitude of this decrease is from 2-5% of the original body weight on the average and has little to do with the duration of the action; it is compensated relatively rapidly by the increase in water consumption and reduced diuresis (Figure 7). A slower restoration of weight and incomplete water retention in a test with a water load for the crew of the "Soyuz-9" spacecraft following their 18-day flight [25] may be explained either by the considerable changes in the sensitivity of the volume receptors /51 or by the fact that the weight losses were linked primarily not with dehydration but with a decrease in muscle mass. The factors that form the basis of muscle atrophy will be discussed in section 2.3.

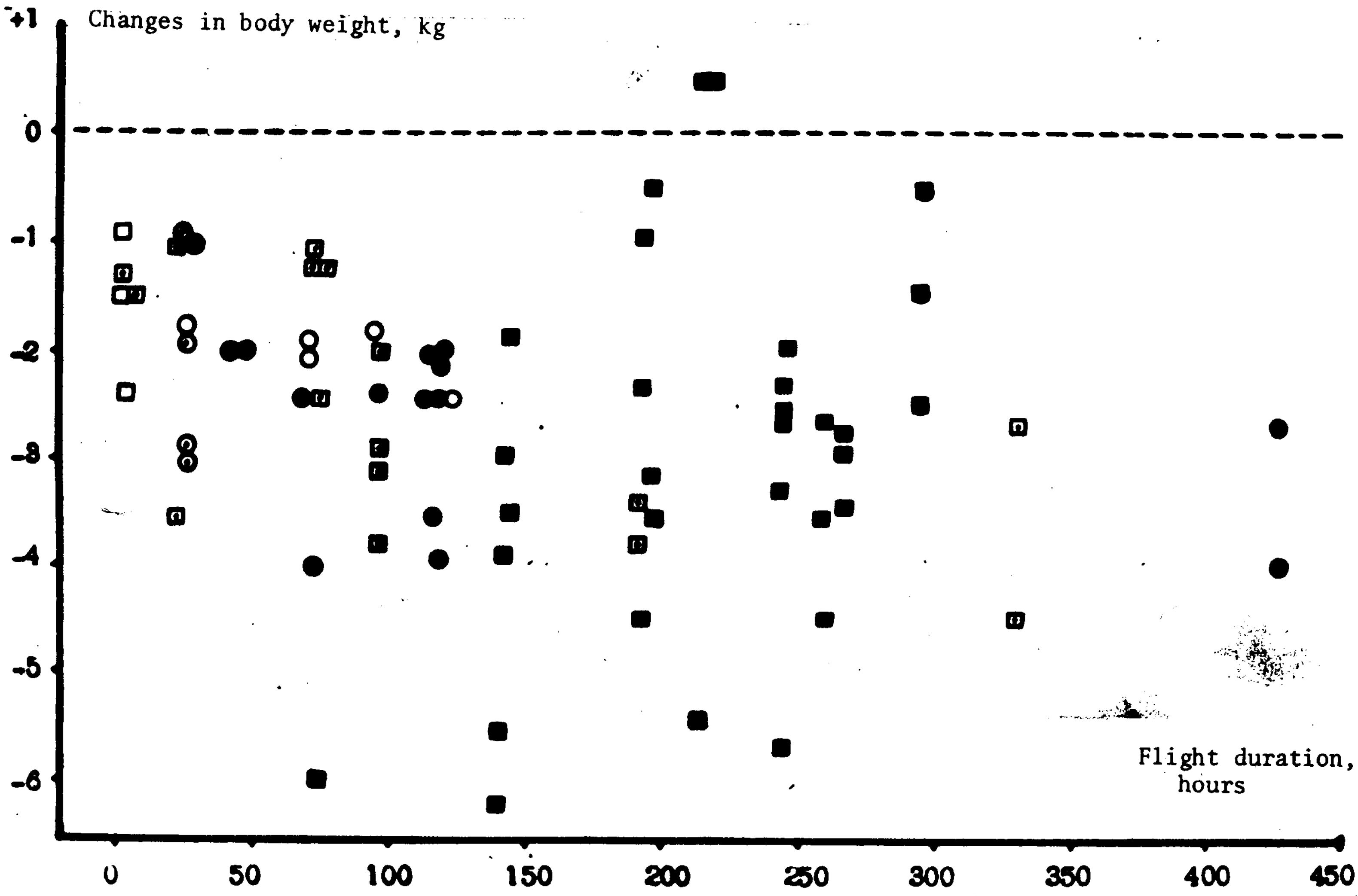

Figure 7. Changes in Body Weight Following Space Flights of Varying Duration

Symbols: Vostok, Voskhod, Soyuz, Mercury, Gemini, Apollo

Still another specific result of the lack of hydrostatic pressure may be the development of changes in venous tone (especially the vessels of the lower extremities), whose regulation under terrestrial conditions is governed primarily by the variations in hydrostatic pressure. In particular, experiments with simulation of weightlessness led to a change in the flexible-elastic properties of the veins when the latter were deprived of this primary stimulus. They become rigid and their distention and contractibility deteriorate [96, 138, 234]. Judging by the latest data, the tendency toward a decrease in distensibility of the vessels of the legs is observed in cosmonauts during the postflight period as well, although it was previously reported that this parameter returned to normal [146, 148].

A regular consequence of prolonged deprivation or decrease of hydrostatic pressure of blood is the deterioration of the postural reaction of the cardiovascular system. The decrease in the orthostatic stability was also observed following the first manned space flights [105, 225]. Later this observation was confirmed repeatedly [29, 143, 171]. The orthostatic disturbances appear systematically as well after studies involving water immersion and bed rest.

The origin of the orthostatic problems is linked primarily to phenomena /52 of dehydration and more precisely to a decrease in the total volume of circulating blood, inasmuch as it intensifies the decrease in the return of venous blood to the heart with the body in a vertical position. It must be kept in mind that dehydration of any origin (blood loss, limited water use, thermal stress) has a negative influence on the tolerance to influences associated to redistribution of the blood to the lower extremities [190, 199, 239]. It is true that not all authors have found a clear correlation between the degree of dehydration or the decrease in the volume of the circulating blood on the one hand and the severity of the orthostatic disturbances on the other, from which we can conclude that this mechanism is not the only one that takes part in the formation of orthostatic instability [96, 163, 257, 268]. The decrease in muscle tone, particularly in the lower extremities, is also quite important in the origin of orthostatic problems that arise following a stay in weightlessness or under conditions simulating it [49, 169, 220, 238]; the capacity of the venous deposit in the lower half of the body [96, 138, 234]; the permeability of the vascular walls and the loss of plasma into the intercellular spaces [169, 269]; the characteristics of the neuro-humoral regulation of the functions in the vertical position and fatigue [85, 96, 163, 191, 218, 232, 250].

In view of the fact that the phenomena associated with orthostatic instability were very pronounced after the 18-day flight of the crew of the "Soyuz-9" spacecraft [55], considerable practical significance attaches to the timely diagnosis of potential orthostatic instability. This can be accomplished by using functional tests associated with measured limitation of the return of venous blood to the heart. It has been found in particular that there is a /53 high degree of correlation between reactions to the orthostatic test and the Valsalva test [167]. The test involving the action of negative pressure on the lower half of the body is particularly informative [35, 208, 239, 275]. This test may be performed during the flight itself and is used actively in preflight and postflight testing of cosmonauts [36, 147, 148].

Dehydration caused by the lack or reduction of hydrostatic pressure of blood apparently is also one of the reasons for deterioration of tolerance to a number of other stressful influences, particularly accelerations and physical stresses. In any case, experimental dehydration to an extent that amounts to more than 4% of body weight, according to the data of Greenleaf et al., led to disturbances involving the isometric muscle contraction, physical working capacity and tolerance to longitudinal accelerations (+ G_z) [199].

These data confirm that the end effects that result from the mechanism of redistribution of the blood in a state of weightlessness are very serious. Therefore, one can understand the considerable emphasis which is placed at the present time on the development of measures for prevention of changes associated with the lack of hydrostatic blood pressure in weightlessness.

3. Reactions of the Organism Associated With the Lack of Weight Stress on the Bone and Muscle System /54

Elimination of weight stress from the support-motor apparatus under conditions of weightlessness serves as the positive factor for a number of systemic changes whose pathophysiological basis is "disuse".

The lack of a need for active opposition to gravitational forces and maintenance of posture, decrease in muscle effort to move the body and its individual parts in space, on the basis of theoretical considerations alone, necessarily leads to a decrease in energy exchange and a decrease in requirements for oxygen transport in the system. Insufficient loading of the muscle system and supporting structures, significant restructuring of the motor coordination in the unsupported state also create the preconditions for changes in metabolism, neurohumoral mechanisms for regulation of somatic and vegetative functions and the development of so-called "hypodynamia syndrome".

In long experiments on the ground with controlled limitation of motor activity, especially its spatial (hypokinesia) and force (hypodynamia) components, there is a systematic decrease in basal metabolism ranging from 3-7 to 20-22% [62, 79, 169, 223]. The indirect determination of the level of gas exchange under space flight conditions, carried out by Soviet and American authors on the basis of the results of chemical analysis of the regeneration material, showed a slight decrease in energy consumption to 83.5-97.2 kcal/hr [26, 143]. Individual direct measurements of the level of gas exchange during /55 space flights still will not allow final conclusions to be drawn, since both increases and decreases in oxygen consumption have been found [58, 61].

The decrease in energy metabolism is one of the reasons for the decrease in food consumption. Observations of this kind have been conducted in particular in studies involving use of water immersion and hypodynamia [103, 194]. Use of food by American astronauts making flights in the "Gemini" program varied rather widely from 1,000 to 2,500 kcal/day, while in the "Apollo" program they were 1,680 kcal/day on the average, i.e., they had decreased [143, 148].

Demineralization of bone tissue, which has been frequently recorded in terrestrial experiments involving hypodynamia and following the termination of actual space flights is evidently the consequence of a decrease in the weight load on the skeleton, since a simulation of this load decreases the demineralization [7, 75, 146, 147, 203, 226].

The decrease in the optical density of the calcaneus (heel bone) following flights reached 15-20% in some cases and was somewhat in excess of the values that were recorded for comparable periods of bed rest. In the "Apollo-14" crew the method of photon absorption failed to reveal any symptoms of demineralization of the bones [153].

There are reports which indicate that calcium losses with the urine in a two week period of simulation of weightlessness amounted to 2 grams and that consequently even a 6-12 month stay in a state of weightlessness would be completely harmless to man [170]. In contrast to this point of view, there are theories which hold that the losses of calcium that are caused by a high /56
physiological activity can lead to a number of functional disturbances, particularly involving the automatic nature of the cardiac muscle, conduction of stimuli, coagulation of blood, etc. [51]. In addition, it is also necessary to take into account possible changes in the mechanical strength of the skeleton due to its decalcification [40]. On the basis of comparative physiological studies it has been concluded that the decrease in the weight load on the bone-support apparatus decreases the erythropoietic function of the bone marrow [68].

Insufficient loading of the muscle system, which develops even in cases of brief weightlessness, taking the form of a decrease in bioelectrical activity of the muscles of the neck, back and pelvis [126], results in the development of a number of specific problems. In experiments with hypodynamia and following the termination of space flights there is a decrease in the volume of muscles, particularly those of the lower extremities [81, 85, 121]. Analytical studies performed on animals allow us to qualify this phenomenon as muscular atrophy [41, 91, 102]. At the same time, there is a change in protein metabolism and negative nitrogen balance develops [103, 114, 116]. Resynthesis of protein and the rate of inclusion of amino acids in it likewise decrease [113, 115]. In the postflight period, cosmonauts have shown an increased content of urea in the blood, increased excretion of creatinine in the urine [5, 23, 29] and a decrease in the total potassium content in the organism [150, 151, 153], which also indicates a breakdown of muscle proteins.

We cannot exclude the possibility that it is precisely the development of destructive processes which serves as the cause for the increase in sedimentation rate, the occurrence of neutrophilic leucocytosis in the lympho- and eosinopenia, which are recorded quite frequently in cosmonauts following /57
their return to Earth. On the other hand, these changes may be due to stress reactions during the postflight period. To support this assumption, there has been an increase in excretion of corticosteroids with the urine and an increase in their concentration in the blood serum following flight, in addition to hyperglycemia [81, 106, 107, 116, 146, 148, 153]. On the other hand, during

weightlessness and during the performance of model experiments, a decrease in the activity of the corticoadrenal system has been observed [103, 191, 230, 250, 271].

The nature of the motor activity and nutrition under weightlessness conditions also affect the condition of lipide metabolism, which can be seen from the increase in the content of cholesterol, lecithin and non-esterified fatty acids in the blood [23, 29, 91, 105, 106, 187]. The decrease in the amount of cholesterol in the American astronauts probably had to do with the nature of the diet and the relatively low food consumption [148].

Weightlessness, as well as the experimental hypodynamia, leads to a decrease in the tone of musculature, muscular strength, tolerance and physical working capacity [46, 63, 76, 121, 220, 223]. During the first few days of the recovery period there is normally evidence of serious disturbances of motor coordination with respect to both statics and dynamics [42, 101, 108].

These changes in the support-motor apparatus are the cause of deterioration of tolerance of all those stressful stimuli in which the increased requirements are imposed on the muscle system in particular.

The decrease in muscle tone, physical stress and energy exchange during hypodynamia decrease the requirements imposed on the system for the transport of oxygen and gradually lead to the development of a lack of training of the cardiovascular system with respect to various stresses. In hypodynamia lasting more than 10 days, many authors have observed an increase in the pulse rate at rest, which is characteristic of the detrained condition [50, 86, 104, 261, 266]. The systolic blood volume, according to the data of a majority of researchers, decreases under these conditions, although some hold the opposite view [10, 38, 83, 86, 95, 104, 261]. As far as the arterial pressure is concerned, during the initial period of hypodynamia there is a predominance of the hypotensive type of reaction, while later the hypertensive variety is more prominent [49, 86, 110]. Such changes in the pulse frequency and arterial pressure are viewed by many authors as a predominance of sympathetic effects in the regulation of the cardiac activity due to functional insufficiency of the vagus [80, 98, 104]. /58

During the 18-day flight of the "Soyuz-9" spacecraft, following an initial decrease and subsequent stabilization of the pulse rate in the crew members, which was usually observed on shorter flights, a tendency was observed toward an increase in this parameter during the last week of the stay in weightlessness [25, 54]. The reactions of the arterial pressure showed an initial hypotensive phase, followed by a stage in which the pressure returned to the original level and stabilized [5, 25, 59, 143, 171]. A tendency was also observed toward an increase in the variability of the parameters of the arterial pressure and a flight drop in the pulse pressure [23, 147].

During a prolonged stay in a horizontal position, the electrocardiogram showed position changes, a relative slowing of the intraauricular, atrioventricular and intraventricular conductivity, as well as the $T_{V_1} > T_{V_6}$

syndrome [27, 49, 50]. The changes in phase structure of the cardiac cycle during laboratory simulation of weightlessness usually combine in the symptom complex which has been called the phase syndrome of cardiac hypodynamia [49, 56, 86]. The symptom complex includes the following; lengthening of the phase of isometric contraction, shortening of the expulsion period, the decrease in the rate of rise of intraventricular pressure, intrasystolic index and an increase in the myocardial stress index. In pathology this syndrome is encountered in various forms of myocardial ischemia and reflects a disturbance of its contractility. Although several weeks are required for development of the above mentioned symptoms of their detraining effect of hypodynamia on the cardiovascular system, some of them have already become evident to varying degrees during the periods of time spent in weightlessness thus far. /59

The electrocardiographic studies that were performed under space flight conditions showed no significant changes in the peaks and intervals of the EKG. The majority of indices changed as a rule in accordance with the changes in pulse rate or reflected the position changes. A number of authors have mentioned, admittedly, that there was some lèngthening of the period of time for auricular-ventricular conductivity and a tendency toward a decrease in the amplitude of the T spike, indicating a deviation in the function of conductivity, as well as in the intensity of the metabolic processes in cardiac muscle during weightlessness [88, 94, 107]. During space flights, individual phasal changes have also been observed which could be viewed from the standpoint of a decrease in the mechanical activity of the cardiac muscle [4, 88]. These include the following: a decrease in the amplitude and duration of the oscillatory cycles of seismocardiogram, an increase in the electromechanical delay, the mechanoelectrical coefficient and the mechanosystolic index. The /60
increase in the electromechanical delay, caused in one of the cosmonauts aboard the "Gemini-5" was linked by the authors with a vagotonic reaction [173, 264]. Symptoms of a deterioration of the contractile function of the myocardium were recorded in cosmonauts soon after their landing [23, 107].

Hence, elimination of the weight load on the bone and muscle apparatus is a distinctive and very important causative mechanism in the development of various disturbances attributed to weightlessness. Some authors even tend to give it the primary responsibility, although this leads to an insufficient evaluation of the role of other pathogenetic mechanisms [53, 220]. Hypodynamia is widespread in clinical practice and even in daily life there is an analogy to this mechanism. Therefore problems of investigating the influence of hypodynamia on the organism and combatting its consequences are not limited to the area of space medicine but have general clinical significance as well.

4. Limitations Based on the Influence of Prolonged Weightlessness on the Human Organism

Reactions that are produced by the influence of weightlessness on the function of afferent systems, distribution of blood and load on the bone and muscle system essentially reflect the accommodation of the organism to new conditions in the environment which proceeds along paths that could be referred to as "disuse" or "atrophy from inactivity". Prolonged weightlessness can lead to the development of destructive processes, a drop in the functional capacities of the organism and its resistance to various stress effects. In this connection, it is advantageous to consider certain of the final reactions that can limit or reduce the effective role of man in the further conquest of space. /61

Asthenization is among the most general symptoms of an unfavorable influence of weightlessness on the organism. Its individual symptoms (deterioration of working capacity, rapid fatigability) are observed in the course of the flight itself [23, 107]. However, the phenomena of asthenization are manifested in a much clearer form upon return to Earth. A decrease in body weight, muscle mass, mineral saturation of the bones, as well as a decrease in strength, tolerance and physical working capacity all limit the tolerance of stressful influences that are characteristic of this period: g-forces and the effect of the Earth's gravitation [107]. In particular, following the 18-day flight, the sensation of weight was felt by the crew members as a force of 2-2.5 G; general weakness developed, dizziness, increased fatigue [25]. The American cosmonauts noted that after the flight even their clothing seemed much heavier to them [147].

Studies involving laboratory simulation of weightlessness which produce the symptoms of general physical detraining in the subjects demonstrate quite clearly the possibility of asthenization of psychic functions. During periods of hypodynamia of three weeks or more there was a quite frequent development of restlessness, irritability, fixed ideas, conflict situations, and in some cases even psychic disturbances were noted [8, 249]. Although the experience of those who have undergone space flights did not reveal any significant limitations associated with such disturbances, a further increase in the length of flights may cause changes of a general psychic and emotional nature, affecting the moods and working capacities of the cosmonauts. These phenomena /62 of general asthenization therefore may act as factors capable of limiting the safety and effectiveness of long space flights to a certain degree.

Disturbances of motor functions under space flight conditions are apparently not critical, since the development of habits of motor coordination in weightlessness take place relatively easily. The problems involving coordination of motion that can develop in the readaptation period are much more unfavorable. In a rough form, these problems have developed in studies involving prolonged bed rest as well as in a serious form following the 18-day space flight [25, 42, 101, 108].

Considerable changes in physical working capacity and tolerance can also seriously limit the ability of the cosmonauts to move around after the end of a flight. Since the magnitude of the coordination problems is a function of the duration of the exposure to hypodynamia and weightlessness, they must be taken into account as one of the important limitations on the path to further increases in flight duration.

Orthostatic instability, which takes the form of a pronounced increase in the physiological state of the changes, development of dizziness, weakness, nausea, and particularly the development of a faint condition in the vertical position, constitutes a very serious problem which is characteristic of the postflight period. While the symptoms of orthostatic instability that are observed following brief flights were short and easily overcome, after the 18-day flight they occurred even in a sitting position and were characterized by considerable duration [55, 143]. /63

It is true that a comparison of the results of the 14-day flight of "Gemini-7" with the shorter flights does not support the existence of any relationships between the severity of the orthostatic disturbances and the duration of the exposure to weightlessness [146]. Preliminary data from the medical examination of the "Skylab" crew following their 28-day flight also indicates that the orthostatic problems in two of the three astronauts were very moderate. Hence, disruption of stability in the vertical position is a function not only of the duration of the action of weightlessness but also such factors as living conditions and the use of protective measures in flight.

Changes in the immunological reactions and the resistance to infection were noticed in experiments involving simulation of weightlessness and after an 18-day space flight [25, 78, 125]. Linked to general asthenization and metabolic changes, these alterations were accompanied by an increase in sensitivity to diseases, which could lead to the development of a critical situation during the flight [33]. Illness can also be transmitted from one crew member to another through the transfer of pathogenic microbes and fungi [148]. The possibilities of using medicinal therapy under these conditions may be limited by the assumed change in the reactivity of the organism with respect to pharmacological preparations as the result of the action of weightlessness [17, 18]. On short flights, no significant changes involving the immunological reactivity were observed [1].

Neurological problems have been recorded during prolonged (more than 30 days) hypodynamia [85]. They took the form of development of symptoms of interhemispheric asymmetry and dextrolateral pyramidal insufficiency, and were linked to problems involving the hemocirculation in the brain and changes in the level of afferent impulsation [77]. It is possible that similar problems could arise on long flights [82], involving in particular a deterioration of motor function and working capacity. /64

Changes in the coagulability during prolonged ground studies involving simulation of weightlessness involve the development of the hemophilic reaction [44, 118]. During the postflight period, some of the cosmonauts developed a condition in which there was a decrease in the number of thrombocytes in the blood [81, 105, 106], which is also indicative of a hemophilic change. In addition, the coagulability of the blood is a function of more complicated relationships between the coagulatory and anticoagulatory systems. It is necessary to consider the possibility of unidirectional changes in both components, which took place in particular in the experiments aboard the "Cosmos-110" biosatellite [3]. The question of how important the problems involving the coagulability of the blood in a state of weightlessness are deserves further research.

There is a definite probability that certain other changes in the functional condition of the organism may limit the length of a safe stay under prolonged weightlessness conditions. Some of them are determined by the processes of restructuring of the mechanisms of nervous and hormonal regulation of the vegetative and motor functions in this state. Others depend upon the degree of structural changes (for example, muscle and bone tissue), the detraining of the cardiovascular system and metabolic changes. However, for the /65 periods of weightlessness that have been undergone thus far, the most critical form of these changes consists of the problems which arise in the readaptational period. Most important of them is the decrease in the tolerance to g-forces, vertical posture, deterioration of physical working capacity and coordination of the basic motor activities. Therefore, one of the most important problems in medical safety on long space flights is the development and introduction of a system of measures aimed at preventing these problems.

III. METHODS OF PROTECTING THE HUMAN ORGANISM AGAINST THE UNFAVORABLE EFFECTS OF WEIGHTLESSNESS /66

1. General Approaches to The Development of Preventative and Therapeutic Measures

In evaluating the phenomena associated with the unfavorable influence of weightlessness on the human organism, it has been found necessary to create conditions for the cosmonaut in which he will not suffer from the effects of physiological and psychobiological adaptation to weightlessness. There are two general concepts with respect to the problem of prevention, which, as we pointed out earlier, are currently in a stage of development [162, 248]. One concept consists in preventing the adaptation of the organism to weightlessness. The other consists in protecting the cosmonaut against undesirable consequences of partial adaptation. At the present time, there is no clear consensus as to which of these approaches is more effective. Preventing adaptation to weightlessness, strictly speaking, can only be ensured by developing a constant and sufficiently complete equivalent of terrestrial gravitation aboard spacecraft. The introduction of artificial gravitation appears to be the most radical method of prevention, but at the present time we still have not accumulated a sufficient volume of data to use in carrying out this complicated and costly solution. In particular, the rotational mode involves a number of technical problems that arise as the radius of the rotating platform increases. In addition to the weight limitations, such problems as the complexity of the orbital design, the gravitational gradient of rotation, retention of a stable orbit, fuel problems, as well as control and supplies remain nearly insoluble. No estimate has yet been made of the /67 possible side effects of prolonged stays in a constantly rotating system which would allow the advisability of developing one to be evaluated. In the final analysis, it may turn out to be necessary to resort to this method of prevention, so that individual theoretical and experimental studies are going forward [31, 130, 152] although both engineers and specialists in biology and medicine are trying to get around it [228].

Practically speaking, the second concept is more realistic for current needs of cosmonautics, since it allows a partial adaptation of the organism to weightlessness but also provides for measures than can be taken to prevent or reduce the principal unfavorable consequences of adaptation.

In any case, the solution of the problem will be satisfactory if the preventive measures employed by the crew during the flight and directly after landing promote preservation of their health and working capacity. The extent of the preventive effects of the protective substances therefore will be based primarily on the maintenance of a sufficient level of physical working capacity, motor coordination and orthostatic stability, inasmuch as changes in these functions during the postflight period appear on the basis of current data to be the most critical. It is possible that such measures will be comparable in terms of technical and operational characteristics with flight conditions and from the medical viewpoint will not produce discomfort or harmful side effects.

The most promising trends in the preventive measures area are governed by those concepts regarding the mechanisms of formation of changes in weightlessness, which we are dealing with at the present time. Using a rather simplified system of pathogenesis for disturbances caused by the existence of weightlessness, we have outlined some of their possible trends and methods of prevention (Figure 8). /68

Evidently the most natural and practically feasible thing is to use preventive measures against such primary causative effects of weightlessness as the elimination of the hydrostatic pressure of the blood and the loss of the weight load on the bone and muscle apparatus. In the event that it is possible to block the development of these primary effects sufficiently reliably, the long chain of secondarily produced modifications would be interrupted, including those which cause the maximum trouble in the readaptation period. Selecting a method for offsetting those changes which occur in the activity of the afferent systems during weightlessness is much more complicated. Some preventive measures (for example, negative pressure on the lower half of the body), causing a stress in the direction of the lengthwise axis of the body and promoting a flow of blood to the legs theoretically can create sensations that are characteristic of a vertical posture [36]. However, it is impossible to eliminate gravitational stimuli for specific gravity receptors which does not lead to the development of artificial gravitation.

The preventive and therapeutic measures can be directed not only at the primary or causative effects of weightlessness but also the lower levels of the pathogenetic chain, represented accordingly in Figure 8.

A more detailed list of the preventive measures used in the course of ground experiments involving simulation of weightlessness and partially suitable for use on real flights is found in Table 6. In this list, we have used the principle of classification of preventive measures based on their physical nature. /69

Within the system of measures aimed at prevention of unfavorable influences on the organism by prolonged weightlessness, particular significance is placed on measures aimed at preflight selection and training of cosmonauts, as well as methods and means of restorative therapy which can be used in the postflight period. However, since these materials have been dealt with in great detail in special chapters of this work, in the following we shall discuss only those means and methods which are designed for use on space flights and immediately afterward. In order to achieve a systematic arrangement of the experimental data obtained in the testing of the individual preventive measures, it would be advantageous to use their pathogenetic effects as a basis.

2. Methods and Means of Preventing the Primary Consequences of a Lack of Hydrostatic Pressure of Blood in Weightlessness

The most logical way of preventing the consequences of unusual distribution of blood associated with a lack of hydrostatic pressure consists in the utilization of means and methods of artificially creating the effects of hydrostatic pressure. For this purpose, experiments using water immersion and prolonged bed rest have been used to test many methods and devices.

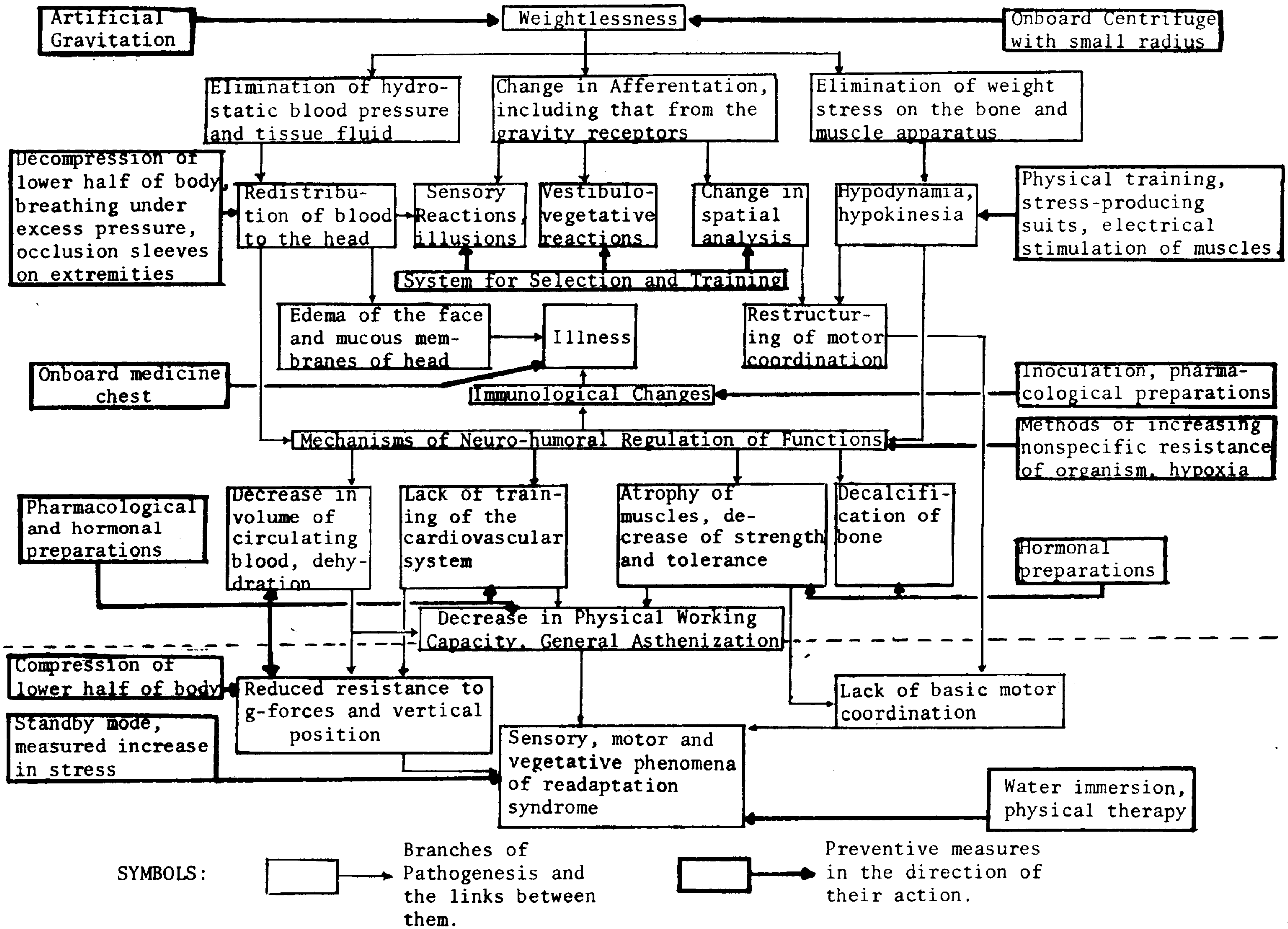

Figure 8. Diagram of the Pathogenesis of Problems Caused by the Influence of Weightlessness and the Directions of the Preventive Actions (Modified Version of the System in the Work by A. M. Genin and I. D. Pestov, 1971).

TABLE 6. MEANS OF PREVENTING UNFAVORABLE CONSEQUENCES OF PROLONGED WEIGHTLESSNESS /70

1. With partial adaptation to weightlessness:	
Physical Exercise	Accelerations
Gymnastics, various forms of sport Diving, tumbling and other forms of training in weightlessness. Exercises with isometric and isotonic muscle contractions. Bicycle ergometers, treadmills and expanders. Exercises involving movements of the head in weightlessness.	Onboard centrifuge. Trampoline (shock-type g-forces) Vibrating support. Vibrating bed (couch). Rotation of the space station.
	Regulation of External Environment
	Hypoxia Decrease in temperature. Standardization of the diet.
Pressure	Pharmacological Preparations
Breathing under pressure. Inflated cuffs. Elastic underclothing. Negative pressure on the lower half of the body. G-suits	Aldosterone Antidiuretic hormone Means of increasing plasma volume 9-Alphafluorohydrocortisone Restorative preparations Glucose Pitressin Anabolic hormones
Electrical Stimulation	
2. With total adaptation to weightlessness:	
Preliminary training of the organism for conditions of reduced weight or condition of weightlessness. Restoration of the training of the organism with respect to the action of normal terrestrial gravitation.	

The use of inflated cuffs, which surround the perimeters of the extremities is aimed primarily at reducing the return of venous blood to the heart and simulation of conditions characteristic of a human being in a vertical position on Earth. Usually narrow cuffs are used, applied to the upper part of the thigh [20, 36, 196, 238, 257, 267]. The pressure levels produced in them usually do not exceed 70-75 mm Hg and the ratio between the length of the periods of compression and the intervals between them vary in different experiments over a rather broad range: from 1:1 minute to 5:10 minutes. The results of numerous laboratory tests of this preventative measure on the whole do not indicate a reliable and clearly reproducible protective effect, although in some instances this effect was in fact observed. The use of cuffs during space /71 flights also failed to yield positive results [171]. Impeding venous efflux when using thigh cuffs in an experiment involving 70 days hypodynamia increased the tensility of the vessels in the legs in comparison with observations conducted under analogous situations but without the use of the cuffs [20, 96]. The reserve capacity of the venous deposit increased and with the body in a vertical position a relatively large amount of blood accumulated in the legs. As a result, orthostatic problems were not eliminated. Hence, physiologically unpleasant side effects of the occlusion method predominated over those effects for which it was intended.

Breathing under excess pressure (on the order of 200-300 mm water column) promotes expulsion of the blood from the lesser circulation into the greater, restriction of the return of venous blood to the heart, as well as prevention of atelectases of the lungs caused by stagnation phenomena in the vessels of the lesser circulation [36, 212, 223]. In those cases when respiration under excess pressure was combined with compensatory counterpressure on the head and upper part of the body, the blood was redistributed to the lower part of the body. This sufficiently adequately imitates the presence of hydrostatic pressure with the resulting consequences. In particular, a g-suit has been described whose use while breathing under excess pressure produces a gradient involving an increase in hydrostatic pressure of the blood in the lower half of the body, so that the level of compensation in such a suit gradually decreases toward the legs [154]. Excess pressure in the lungs during a 6-hour water immersion inhibited diuresis, salt excretion, and prevented orthostatic difficulties [212]. Another important parameter in the characteristics of the method described is the level of the variations in intrapleural pressure during respiration. It has been shown that ventilation of the lungs under "oscillating" pressure increases diuresis [179]. Similar data were obtained in an 18-hour immersion in water to the level of the neck [36]. For 2.5 hours, the subjects breathed in from the atmosphere and breathed out into the water (the resistance to expiration was 200 mm water column). The amount of urine excreted and negative water balance increased while the orthostatic problems were not prevented. In tests involving total immersion in the immersion medium the respiration under pressure equivalent to the external pressure on the chest reduced the severity of the changes in the water salt balance and promoted orthostatic stability [209].

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On the basis of the above we can conclude that the principle of breathing under excess pressure of itself is well founded from the pathogenetic standpoint and is promising. With appropriate structural designs, it could be used more widely in experimental practice and possibly on space flights as well.

The method of producing a negative pressure on the lower half of the body (NPLB) is similar to that described above and differs from it primarily in the nature of the apparatus used [36, 99, 221, 230, 256, 258]. The use of a device that promotes a slight rarefaction of the air around the lower half of the body thereby makes it possible to redistribute the blood as if there was excess pressure on the upper half of the body and the lungs and the lower half was at normal pressure. However, both these methods fall short of simulating completely the characteristics of blood redistribution which is characteristic of the vertical position in which the filling of various parts of the body with blood is a function of the smooth increase in hydrostatic pressure. However, when the pressure change occurs on only one level (for example, around the waist) redistribution of the blood acquires a stepwise nature. Nevertheless, experimental studies have shown that even this incomplete simulation of the hydrostatic factor promotes stagnation of fluid in the organism, normalization /74 of the volume of circulating plasma and orthostatic stability under conditions of laboratory simulation of weightlessness. The levels of the rarefaction acting on the lower half of the body usually amount to 25-50 mm Hg in various experiments (below atmospheric pressure) while the duration of the action is from 1-2 to 10-12 hours per day. Both constant and varying pressure values are employed, as well as daily systems for training or training cycles during the last days of the experimental period. In other words, the search for optimum systems of influence is still going on. In particular, data have been collected which indicate that an increase in ADH secretion and stimulation of the sympathetic nervous system are due solely to a rarefaction of 40 mm Hg or more [247]. It was recently shown that a 15 minute daily exposure to NPLB at a level of 70 mm Hg not only prevents a drop in the orthostatic stability in subjects who were detrained by the conditions of a 5-day water immersion and a stay in bed rest, but also significantly increased the level of this resistance with respect to the original control level [168]. However, lower values of negative pressure obviously can have a positive physiological effect. Thus, the influence of NPLB at the 30 mm Hg level produced the same changes in the activity of renin in the venous blood as did the orthostatic test which was performed at an angle of 70° [177]. In experiments involving the use of water immersion, when the compensatory counterpressure of the water on the lower half of the body was decreased by a total of 24-25 mm Hg, there was an /75 effective retention of fluid in the organism, an increase in body weight and orthostatic stability in seven out of the eight subjects to degrees that were higher than prior to the start of the study [99]. During the NPLB sessions there was an increase in the functional residual capacity, as well as the vital and total capacities of the lungs [174]. By simulating the natural orthostatic mechanisms periodic NPLB sessions can promote the prevention of orthostatic instability in space without using more complicated devices.

Promising results with respect to the prevention of unfavorable reactions were obtained by exposing the subjects to accelerations on centrifuges with a short (about 2 meters) arm, where the g-forces at the level of the head were close to zero and at the level of the legs reached 2-3 units. The effect of longitudinal forces ($+G_z$), developed on such centrifuges, simulate the hydrostatic pressure and simultaneously affect the bone and muscle system and the gravity reception [240, 242, 243, 246]. The use of these influences in experiments involving simulation of weightlessness has led to an increase in ADH, renin and catecholamine secretion, a decrease in diuresis and excretion of salts and a restoration of the volume of circulating blood to normal [242, 243, 246]. The changes in the EKG which were observed under the influence of longitudinal g-forces are linked to an increase in the sympathetic tone [164].

It has been noticed that at shorter arm lengths on centrifuges the working capacity and tolerance to acceleration are less than on centrifuges with relatively long arms [235, 240], which has to do with the considerable magnitude of the gradient of the g-forces acting on the body. After completion of such rotations, certain problems affecting motor coordination developed. In addition, it was observed that a total of only four rotations at a g-force of + 4 G_z (at the level of the legs) of 7.5 minutes each /76 noticeably prevented orthostatic instability if we can judge the latter on the basis of the development of collapse [162, 248]. However, reactions involving the pulse and blood pressure to the static orthotest were not improved very much. The use of rotations on the centrifuge also provides little idea about the decrease in the volume of plasma during prolonged bed rest. Hence, a comprehensive evaluation of the advantages and limitations of this preventative action remains to be conducted. If the need for such devices and the effectiveness is to be sufficiently well established, from the standpoint of weight, energy consumption, size and side effects they can be used for future spacecraft [158].

The use of shock stresses which act in the direction of the lengthwise axis of the body and cause redistribution of the blood along the major vessels can be included to a certain extent among the group of methods discussed here [47, 163, 273].

Preventive actions aimed at certain intermediate branches of the pathogenetic chain can be carried out using pharmacological and hormonal preparations [13, 17, 18, 92, 96, 180, 230, 257]. Substances of this kind have been found effective under conditions of model experiments and have prevented phenomena of detraining and orthostatic instability, which arise following a certain period of remaining in a horizontal position [157, 210]. /77

The restoration of a low volume of circulating blood due to retention of the fluid and salts in the organism may be achieved by a means of a number of hormonal preparations: vasopressin, pitressin, and 9-alphafluorohydrocortisone [157, 170, 211, 275]. Healthy subjects who received 9-alphafluorohydrocortisone for two 10-day periods of bed rest and two 10-day periods of normal (ambulatory) activity had larger volumes of plasma, a more favorable reaction with respect to the pulse rate in the orthostatic test and physical exercises, and the restoration of the pulse rate in them was the same as determined before the start of the test [157]. It is true that not all the preparations were equally effective. The use of pitressin during bed rest and water immersion suppressed diuresis and stabilized the plasma volume but it did not prevent orthostatic instability [211]. A relative increase in the tolerance to gravitational effects following tests using water immersion and prolonged hypodynamia was obtained with the aid of a number of preparations that exert a stimulating effect on the central nervous system, heart and transversely striated musculature (phenamine, caffeine, securinin) [18, 96]. Evidently the use of such preparations on the most important portions of the flight, particularly before landing, is completely justified, regardless of the fact that the reactivity to them under these conditions may vary [104].

In conjunction with conditions of postflight period, for prevention of orthostatic disturbances in cosmonauts, it was recommended that g-suits be worn like those usually worn by pilots [36, 237, 238]. This preventive method /78 promotes a significant decrease (and in some cases, even normalization) of the orthostatic reactions following the termination of experiments involving simulation of weightlessness. Its protective effect consists in the fact that the volume of blood deposited in the lower extremities in the vertical position is reduced. The effect is particularly pronounced in those cases when the prevention of orthostatic instability is accomplished on a complex basis and includes, together with other influences, the use of negative pressure on the lower half of the body during the experimental simulation of weightlessness [36]. Good results were obtained in cases when pressures on the order of 35-50 mm Hg were produced in the compartments of the g-suit. Prolonged (up to 10-11 hours) continuous wearing of the g-suits with the compartments inflated was tolerated completely satisfactorily and did not lead to the development of local or general unfavorable reactions. The use of an elastic undergarment (leotard) that exerted pressure on the lower half of the body also had a favorable influence on resistance in the vertical position in both healthy individuals and those who had been detrained following prolonged bed rest [270].

Another theoretically possible way of relieving orthostatic stress in the postflight period might consist in establishing a backup system with gradual, measured increase in time spent in the vertical position. In particular, positive effects have been described that were obtained by orthostatic training that consisted in alternating 30 second passive changes in the position of the body from 45° (head down) to 90° (head up) [236]. /79

Hence, the results of laboratory studies indicate that prevention of the principal consequences of a lack of hydrostatic pressure under conditions of weightlessness and particularly orthostatic instability is quite possible. Feasible methods of solving this problem consist in using the action of negative pressure on the lower half of the body at the end of the flight, the use of pharmacological stimulants one hour prior to descent from orbit, use of a "g-suit" immediately after landing, as well as the use of correct procedures in the readaptation period.

3. Methods and Means of Preventing the Most Important Consequences of Hypodynamia

Making up for the deficit of weight stress on the bone and muscle apparatus under conditions of weightlessness by means of other stress producing methods is one of the very important trends in the development of preventive measures. Although the use of such procedures involve the need for additional oxygen, food and electrical energy supplies aboard the spacecraft, which is not totally optimal from the purely technological standpoint [260], medical arguments in favor of the introduction of this approach to treatment are quite convincing.

The rich volume of experience that has been accumulated in such areas of knowledge as the physiology of sports, sports medicine, physical exercise to improve condition and for therapeutic purposes, constitute eloquent proof of the diverse favorable effects of physical exercise particularly if devised on an appropriate methodological basis and organized into a planned training process. /80

In a situation when the insufficiency of muscle stress is a reason for the development of unfavorable changes in the condition of the organism, the use of means and methods of physical training is not only justified but necessary. The use of a measured volume of physical exercise in studies with controlled limitation of motor activity, its spatial and force components has promoted normalization of a number of phenomena associated with the hypodynamic syndrome. Changes involving gas exchange [62, 79], nitrogen metabolism [113], the cardiovascular system [74, 95, 104], neuro-psychic functions [8, 76, 85, 249] and immuno-biological reactivity [125] have been less prominent in this case. The positive action of physical training has also been observed in connection with the state of the bone and muscle apparatus, physical working capacity and motor coordination [53, 63, 120, 196] as well as the tolerance of stress [73, 120]. Relatively few effects have been achieved by means of physical training for the purpose of preventing changes in water salt balance and orthostatic problems [12, 53, 163, 196, 238, 268], although in some studies certain positive results have been obtained in this respect [98, 120]. Persons performing physical exercise during strict bed rest for five weeks retained their working capacity and showed no decrease in the renin content in the plasma as a response to stagnation of venous blood in the lower extremities, /81
although cases of development of fainting states during orthostatic tests have occurred frequently [222]. It has been found that when physical exercises are performed during bed rest there is a decrease in the volume of urine, sodium chlorine and creatinine excretion [178]. However, it may be assumed that the retention of fluids and salts may decrease in this case as a result of sweating.

Naturally, in evaluating the results obtained with the aid of physical training, one must take into account the degree of optimality with which the choice of the volume of stresses, training programs, nature and structure of exercises, and training methods employed was selected. Certain advantages are associated with those forms of training which include inertial-shock effects along the lengthwise axis of the body (simulation of jumps in the horizontal position with use of shock absorbers and a solid support for the legs for a reciprocating movement of the bed between two "trampolines") [47, 163, 273]. It is felt that the stimulation of the vessels in the course of performing these exercises, as well as the effects of vibration during bed rest can maintain the ability of the blood vessels to compensate for the decrease in hydrostatic forces with reduced gravitation in a satisfactory fashion. Considerable importance attaches to exercises for the lower extremities as well, since these exercises can decrease the tendency toward stagnation of venous blood in the vertical position due to maintenance of tone, strength and mass of muscles, and /82
possibly the ability of the vasoconstrictive mechanisms to react to the intravascular hydrostatic forces caused by gravitation. In studies involving two months bed rest and various types of exercises, the investigators gave preference to isotonic weight lifting exercises over isometric ones [159]. Nevertheless, isometric exercises also were capable of reducing the muscular atrophy [249]. Their use made it possible to reduce the sensory and motor-muscular stimulation of the CNS and achieved normalization of the psychological functions.

Recommendations as to the necessary volume of physical stress varied rather widely, all the way up to difficult to reach values of 1,000-1,300 kcal/day, while significantly smaller stresses resulted in completely satisfactory results [47, 120]. Most frequently, springs or rubber expanders, bicycle ergometers, "treadmill" type trainers and stress suits that create an axial static stress on the body by virtue of rubber straps are most frequently used for studying the methods of physical training. A description of these methods will be found in the primary sources cited above and in a number of other papers [36, 48, 139]. It is quite clear that relatively better results can be achieved by using such methods and means of physical training which ensure primarily loading of the "antigravitational" musculature, but can harmoniously influence other muscle groups as well. It is very desirable to have this ability to maintain such important motor habits in a state of weightlessness or under conditions which simulate it as walking and running. In a number of ground tests, a training device that consisted of a vertically /83
mounted treadmill to which the subject (in a horizontal position) was attached by means of rubber straps was tested and found to satisfy the above requirements. The trainer imposes a constant static stress in the direction of the lengthwise axis of the body and makes it possible to carry out such exercises as walking, running, jumping, doing sit ups and lifting "weights" under conditions simulating weightlessness. As a result of these studies it was found that the use of this type of trainer promoted significant normalization of motor and vegetative functions and facilitated the course of the recovery period in subjects following 70 days bed rest [33, 36, 47]. In addition, total normalization of symptoms of the hypodynamic syndrome could not be achieved in this study which are observed when other methods of physical training are used [10, 53, 76, 78, 196]. Moreover, several authors found no positive effects whatsoever for physical training involving simulated weightlessness [12, 86, 103, 163, 238, 268]. This is probably an extreme point of view and is explained by the nature of the method of training used or the study of parameters that are linked pathogenetically with the nature of the motor activity to only a slight extent. In addition, we can conclude that prevention of all symptoms of an unfavorable influence of weightlessness cannot be achieved by similar methods but must be devised on a complex basis.

Experience in using methods of physical training under space flight con- /84
ditions is still limited [25, 37, 81, 143, 172], but there is no doubt as to the desirability of its further use in weightlessness. The crew of the "Gemini-7" spacecraft, who performed exercises with isometric contractions, showed changes involving the bone tissue that were less in terms of quantitative parameters determined using radiodensitometry than in untrained cosmonauts [146]. The cosmonauts aboard the "Salyut" orbiting station had a positive opinion of the use of methods of physical training in flight [36]. Preliminary reports indicate the successful and effective use of means and methods of physical training aboard the "Skylab" orbiting station.

The question of the nature, intensity and even the need for increased physical training of cosmonauts during the preflight period is less clear. Opinions regarding this point are partially contradictory. From the purely theoretical standpoint, one might conclude that a physically less trained organism, with all other conditions equal (sex, age, etc.) would adapt better to a shortage of muscular activity than one that was highly trained. It has been mentioned that an abrupt cessation of training on the part of qualified athletes of itself will lead to disturbance of metabolism, the functions of the nervous, cardiovascular and other systems. Similar dangers as far as space flights are concerned are nonexistent in the opinion of some authors [69, 70]. Planned physical preparation for weightlessness conditions is considered necessary, with particular significance being attributed to the general tolerance as a factor that increases the resistance of the organism to prolonged hypodynamia. /85 Reports exist which state that athletes can withstand hypodynamia better than untrained persons and the recovery of the original condition takes place relatively more rapidly in them [49]. In studies involving water immersion, inhibition of the diuretic reaction and a higher degree of resistance to the effects of tests were found in athletes as compared to untrained persons [155]. However, the changes involving proteins and electrolytes in the blood were the same for these groups of subjects [156]. It has been suggested that the reflexes that regulate their volume of fluid have adapted to changes in blood volume in the athletes, since the performance of physical exercise is frequently accompanied by such changes.

Among the contradictory views on the role of the original condition in ability to tolerate stressful influences, we can find mention of the fact that preliminary physical training does not constitute any kind of advantages as far as tolerance to gravitational stresses is concerned (accelerations and orthostatic tests) [166, 216], although according to other data athletes can withstand these effects better than untrained persons [112, 267]. In the "detrained" state and particularly after studies involving prolonged bed rest, the changes in the orthostatic resistance and physical working capacity in athletes showed the same trends and intensity as in untrained persons [267], /86 although the nature and the level of the physical training had a definite effect on the tolerance to hypodynamia [50]. It is felt that the combination of physical exercises with orthostatic training does a sufficiently good job of preparing the organism for the conditions of hypodynamia [236]. Previously trained rats showed higher resistance to hypodynamia only during the initial period of the experiment, while at subsequent stages the changes in the muscular and motor nerve fibers became more pronounced in them than they did in the untrained animals [41].

Hence, the very important problem of determining the optimum level of physical training in the preflight period is still evidently awaiting its experimental solution. In this connection we cannot exclude that recommendations with respect to this problem may differ significantly as far as flights of varying durations are concerned. It is also not completely clear whether or not it will be necessary to correct systems of physical training intended for the flight itself with consideration of the fact that physical condition of the crew will constantly be deteriorating in comparison with the preflight level. In the course of prolonged ground tests, situations occasionally developed in which the amount of stress which was completely satisfactory in the initial stage of hypodynamia became excessive at later stages and led to the development of symptoms of overtraining. It is possible that this question should also be the subject of a special study.

In a system of preventative changes, due more or less to a lack of weight stress on the support-motor apparatus, other methods of affecting various branches of this pathogenetic chain may be used. Electrical stimulation of the muscles, the use of hormonal preparations that normalize protein and calcium metabolism, and various methods of increasing the resistance of the organism to infections appear promising in this respect [92, 103, 207]. /87

Hence, with respect to the prevention of hypodynamic syndrome, there is a completely realistic structural basis which consists in the development of constant and variable stress on the bone and muscle apparatus as well as the use of pharmacological preparations.

Of course, the action of most of the above mentioned preventative measures is not strictly selective but frequently extends to combined branches of pathogenesis and thereby goes beyond the limits of the proposed classification which emphasizes only the primary effects for which a specific measure was designed. For example, the effect of negative pressure on the lower half of the body, in addition to redistribution of the blood, is likewise accompanied by an axial load on the organism, whose magnitude and point of application are determined by the characteristics of the design of the vacuum container used. In addition, decompression of the lower half of the body can create sensations that are characteristic of the action of the force of gravity. The use of a vacuum container during bed rest creates in particular the feeling of being in a vertical position. Another example of a preventative measure that has a broad spectrum of action and is directed essentially toward all triggering mechanisms for changes associated with weightlessness is the use of onboard centrifuges with short arms. Nevertheless, at the current state of our knowledge, not to mention the methodological and technical equipment, the achievement of relatively harmonious preventative effects may be achieved only by using a number of preventative measures aimed at various branches of the pathogenetic chain. /88

4. Methods of Nonspecific Prevention

Within the total system of preventive measures, it is also necessary to take into account the possibility of an increase in the nonspecific resistance of the organism. One of the obvious trends in this direction consists in the decrease of the harmful effects of the stress factors in space flight. For example, the severity of the vestibulo-vegetative symptoms may cause additional dehydration and asthenization of the organism in flight. In this connection, the system for preflight selection as well as the vestibular training of the crew, in addition to measures aimed at stabilization of the spacecraft themselves, may be viewed as one of the conditions that indirectly ensure better tolerance of weightlessness. A decrease in noise level, optimization of temperature, development of appropriate hygienic and living conveniences can also promote this. The use of light clothing to be worn during flight instead of always wearing space suits would decrease the symptoms of the unfavorable influence of weightlessness for a 14-day flight in comparison with one lasting 8 days [143].

Considerable importance as far as prevention of asthenization is concerned attaches to sufficient water usage, complete and well balanced diet. In connection with observations that indicate an increase in excretion of vitamins from the organism during prolonged hypodynamia, vitamin saturation of the diet /89
fed the cosmonauts had to be increased [103]. Data are available indicating the value of additional administration of calcium and potassium in the diet because their losses increased during weightlessness [143, 153]. Judging by the results of ground studies, adding phosphates to the food ration decreases both the excretion of urine and the losses of calcium from the blood serum. The taste characteristics of food and drinks in the diet served aboard the craft must ensure stimulation of an appetite that has been reduced as a result of weightlessness.

The general state of the cosmonauts, weighed down during the flights by intensive professional activity, can depend to a large extent on the development and severity of fatigue. In this connection, it is necessary to consider the need to provide appropriate conditions for rest and especially sleep whose duration during flight (according to certain data) amounts to no more than 5-6 hours a day [143, 147]. For purposes of preventing general asthenization and undesirable changes in mood on the part of members of Antarctic expeditions, Soviet scientists recently tested so-called "recovery preparations", which included the following ingredients: ascorbic acid, glucose, phytin, lipocerebrin, calcium pangamate, thiamine bromide, methionine, calcium pantothenate, nicotinic acid, riboflavin, glutaminic acid and elenium [213]. By means of an EEG it was established that these preparations reduce the severity of the unfavorable changes involving brain activity as well as the behavior of individuals which occur under the influence of prolonged exposure to conditions of sensory deprivation and stress. Although these results were obtained under terrestrial conditions at low altitudes, associated with moderate hypoxia, the /90
possibility of using them on space flights must be considered.

The role of additional factors that intensify the reaction of the organism to weightlessness can also be evaluated on the basis of the results of studies performed aboard biosatellites [91, 135, 233]. Rather serious problems that were observed in experimental animals during these experiments evidently were not caused by weightlessness alone but also by conditions involving rigid immobilization, loss of appetite, and isolation. It may be that the decrease in the harmful effects associated with space flight likewise decreases the unfavorable influence of weightlessness on the organism.

Another possible approach to increasing the nonspecific resistance of the organism to the action of weightlessness may consist in using the measures aimed at hardening, widely used under terrestrial conditions, using general ultraviolet irradiation and acclimatization to high altitude conditions [15, 19, 72, 219]. In experiments involving simulation of weightlessness, the action of hypoxia prevented the decrease in the mass of erythrocytes, but did not prevent plasma loss [256]; there was also a decrease in the excretion of electrolytes, total nitrogen with the urine and demineralization of bone tissue [226]. Physiological reactions to hypoxia are viewed as counter reactions in the hypodynamic syndrome and are similar to reactions to physical training [219, 262]. It is obvious that in the total picture of preventative measures, periodic changes in the gas composition and other parameters of the environment may find justifiable usage in time [34].

These methods of nonspecific prevention are being used in part in modern programs for space exploration. Increasing the internal volume of spacecraft and creating improved living conditions aboard them is contributing markedly to a reduction of unfavorable reactions to weightlessness. However, the potential for increasing tolerance to this space flight factor has been far from exhausted and the search for effective methods of nonspecific prevention must go on. /91

In winding up our discussion of experimental data characterizing the practical possibilities of preventing unfavorable influences of weightlessness on the human organism, we must mention once again that the successful solution of this problem can be achieved by means of a number of preventive measures that affect various branches of the pathogenetic chain.

Initial experience in testing such a combination during the flight of the "Salyut" orbiting station indicates that selective approaches and structuring of preventive measures was adequate [36]. The crew willingly used these devices, including a trainer for physical exercise, a vacuum container for the lower half of the body, and g-suits. Although it is not possible now to evaluate the effectiveness of these measures, it must be pointed out that the first practical steps toward the achievement of further progress in this field of space medicine have already been taken. The success of the complex approach to devising a system of preventive measures, judging by the preliminary reports in the press, was clearly demonstrated on the 28 and 59-day flights of the crews aboard the "Skylab" orbiting station. However, still more effort and time will be required for a final solution to the problem of prevention of the unfavorable influence of prolonged weightlessness. /92

CONCLUSIONS /93

The results obtained during the space flights and laboratory studies that have been completed have shown that man is capable of withstanding the effects of reduced weight or weightlessness for several weeks. Already in the course of the first decade since the beginning of the conquest of space by man, more than 50 astronauts and cosmonauts have participated in flights that add up to more than a year in all. This means that weightlessness has ceased to be a mysterious and hidden factor in many respects. Scientific facts which have made it possible to discard a number of false threats and discover the existence of real ones resulting from the influence of weightlessness on the human organism, have replaced a variety of hypotheses. However, the most important characteristic of scientific research, related to weightlessness, has been not only the analysis of results of previous flights but also the determination of the possibility of further increases in their duration.

A retrospective analysis of the state of the art indicates that the level of scientific theoretical thought at all stages of development of cosmonautics has been sufficient to satisfy the practical requirements in a timely fashion. Long before the practical need for eliminating the unfavorable effects of prolonged weightlessness on the human organism arose, laboratories in the USA and the USSR had already begun testing effective preventive measures. It was precisely the development of these measures that makes it possible at the present time to plan for space flights of increasing duration. However, as the length /94 of the flights increase, new problems may arise. This fact makes even more important the significance of further studies linked to the effects of weightlessness on the human organism.

In this connection, four areas of medical biological research have been defined. The first consists of a study of the mechanisms which lead to disturbances involving the cardiovascular system as well as changes in the density of the bones and the muscle mass, changes in the fluid volume in the organism, orthostatic instability, reduced physical working capacity and general asthenization. The duration and final results of these disturbances have still not been established.

Serious attention must be paid on an ongoing basis by researchers to the study of the circulation of the blood during weightlessness. Increased filling of the vessels in the lesser circulation with blood in the absence of hydrostatic pressure can theoretically lead to spasms of the arterioles, increased pressure in the pulmonary artery (Kitayev reflex) [64] and an increase in the load on the right ventricle. Since this theory is in agreement with experimentally obtained data concerning the increase in central venous pressure in monkeys in a state of weightlessness and with the electrocardiographic recordings indicating an increase in the load on the right ventricle during bed rest, the possible consequences of these circulatory changes must be subjected to a clinical-physiological evaluation.

The second area involves the nerve-reflex and sensory changes associated with the state of weightlessness or the transition to it. Particular

attention should be paid to cases of development of motion sickness which /95
depends primarily on the vestibular reactions to weightlessness. Although some cosmonauts have noticed a deterioration of their mood during space flight, they recovered during the period of time they were exposed to weightlessness. The relationship between individual tolerance to motion sickness on Earth and in weightlessness is still not clear. The combined effect of weightlessness together with other environmental conditions such as microclimate, sensory deprivation, limited mobility and emotional factors, is still unclear. In this connection, it is necessary to study and check various concepts and models of synergism.

The third area of study involves processes of adaptation to weightlessness, particularly evaluation of dynamics and possible consequences. On the basis of experimental and theoretical data, various systems and functions of the organism have been defined which influence the adaptation process. The experience of terrestrial studies involving simulated weightlessness indicate that during a period of 1-2 months the process of adaptation is stabilized to a large extent, although there is a simultaneous increase in the danger of new limitations which may arise in the course of the flight itself. These limitations may include greater possibility of illness than previously [134], particularly in connection with a decrease in immunity, as well as a development of changes in the neuro-emotional sphere. Changes in the readaptation period of a qualitative nature probably will not differ significantly from what is already known in this respect. However, the quantitative nature of a number of changes (for example, demineralization of the bones, muscular atrophy, etc.) may increase if appropriate preventive measures are not taken. /96
In short, a prediction based on the results of model experiments will doubtless require further refinement and correction on the basis of results of actual flights of increasing duration.

At the present time, schematic models of the adaptation process have been devised in which many of the currently available data can be sorted out into a logical relationship. As new information is gained, these models obviously will make it possible to determine more precisely the role of the responsible mechanisms that form the basis of the adaptation process and will thereby supply important information necessary for effective prevention and therapy. Inasmuch as the data obtained under laboratory conditions and during flights correlated with one another we can conditionally answer the question of the adequacy and value of the experiments simulating the state of weightlessness which are performed on Earth.

The fourth area of research includes development, testing and improvement of systems for preventing the unfavorable influence of prolonged weightlessness on the human organism for the purpose of increasing the safety of flights, the working capacity of the crew and the effectiveness of space missions. On the basis of available data we can conclude that the degree of adaptation of cosmonauts to weightlessness and the deterioration of tolerance to gravitational effects that results from it may be regulated in different ways. The program of medical preventive measures which is planned for long space flights are combinations of effective protective measures and can eliminate the need for artificial gravitation aboard the spacecraft. However, in order to have a timely use and standardization of preventive effects, it is necessary to continue the studies aimed at working out optimum methods of medical monitoring of the condition of health of the crew members in future space flights. /97

In order to obtain adequate information on the problem of weightlessness, it is necessary to develop an appropriate program of scientific research and to carry it out both on flights and under terrestrial conditions. It is necessary to put together a more accurate system of measurement which will correspond to equipment and instruments used for studies during flights as well as to invent and introduce into practice new informational functional tests. It is necessary to continue the discovery of biological factors upon which the development of processes involved in the detraining of the organism during weightlessness depend as well as the restoration of the functions of the organism. Since the reliability of the "human factor" on long space flights is equally important as the reliability of space technology, we can only hope that scientifically well founded methods of solving medical and biological problems that follow from the influence of prolonged weightlessness on the human organism will be found and utilized in time.

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16. Abstract

The historical development of gravity reception is traced in terrestrial life forms, including man. Examples of the effects of the "unnatural" state of weightlessness on bones, muscles, organs and body fluids are presented, with particular stresson those modifications that can be viewed as accommodative. Experimental procedures such as the application of negative pressure to the lower half of the body and periods of prolonged bed rest (hypokinesia) are evaluated in terms of their effects on the tolerance to stress. Guidelines are developed for the prevention of deleterious effects of weightlessness on man in space.

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